Effect on GPS Signals due to the Ionosphere Near the Geomagnetic Equator

Thomas Dehel
FAATC ACB-430
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Effect on GPS Signals due to the Ionosphere Near the Geomagnetic Equator

- Introduction
- GPS Satellite Basics
- GPS Augmentation with SBAS
- WAAS Iono Algorithms and CONUS conditions
- Geomagnetic Equator Ionosphere Conditions
- Future Plans – Second Civil Frequency

Augmentation of GPS

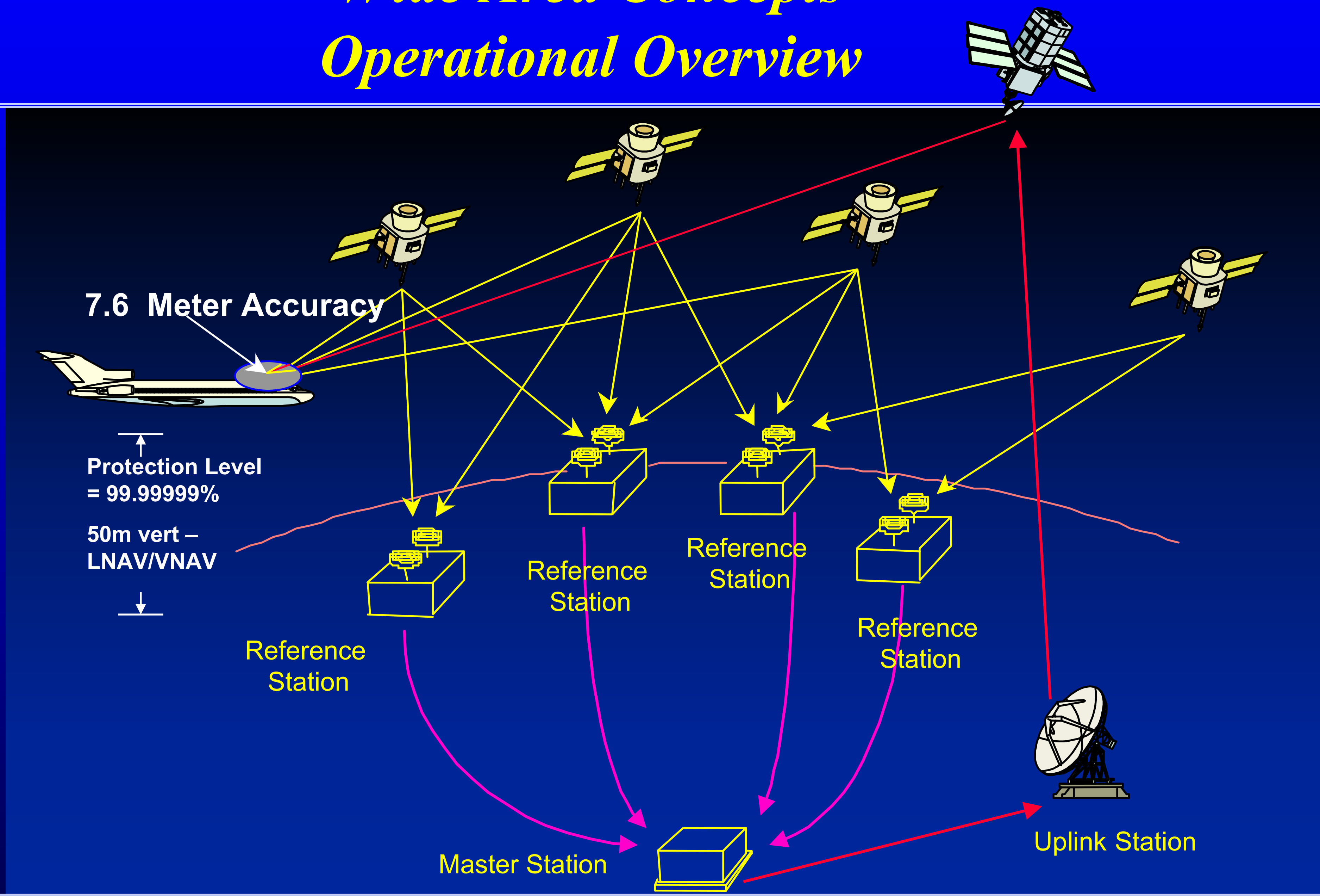
- FAA needs to “augment” GPS to remove errors and add availability and integrity
- Two basic concepts – local area & wide area
- Local Area Augmentation System (LAAS) monitors and generates corrections as seen from same airport
  - This lumps satellite clock error, ephemeris error, and iono error

    into one correction valid ***at that location***

GPS Augmentation

- SBAS – Space Based Augmentation System
  - Designed to identify and correct for specific errors, ***valid over wide area***:
    - Satellite Clock (formerly included SA)
    - Satellite Ephemeris
    - Ionosphere
    - Bounds-of Error on all corrections to guarantee safety!
      - **UDRE – User Differential Range Error – bounds clock and orbit errors**
      - **GIVE – Grid Ionospheric Vertical Error – bounds ionospheric error**

Wide Area Concepts Operational Overview



SBAS Basics - HPL and VPL

- UDRE – User Differential Range Error – a 99.9% bound on satellite clock and orbit error
- GIVE – Grid Ionospheric Vertical Error – a 99.9% bound on Iono Grid Point ionospheric delay

- HPL – function (DOPs, receiver noise, UDREs, and Iono Variance or GIVEs)
- HPL is a 99.99999% (5 sigma) bound on horizontal position error

- VPL – function of (DOPs, receiver noise, UDREs, and GIVEs)
- VPL is a 99.99999% bound on vertical position error

SBAS Basics

- If vertical position error is greater than VPL the result is or Horizontal Error is greater than the HPL, the result is:
  - **HMI …… Hazardously Misleading Information**
  - **user *unaware* of incorrect position**
  - **Flying without runway in sight, aircraft could be too high or to low at wrong location**
  - **The User *trusts* WAAS to provide safe information**

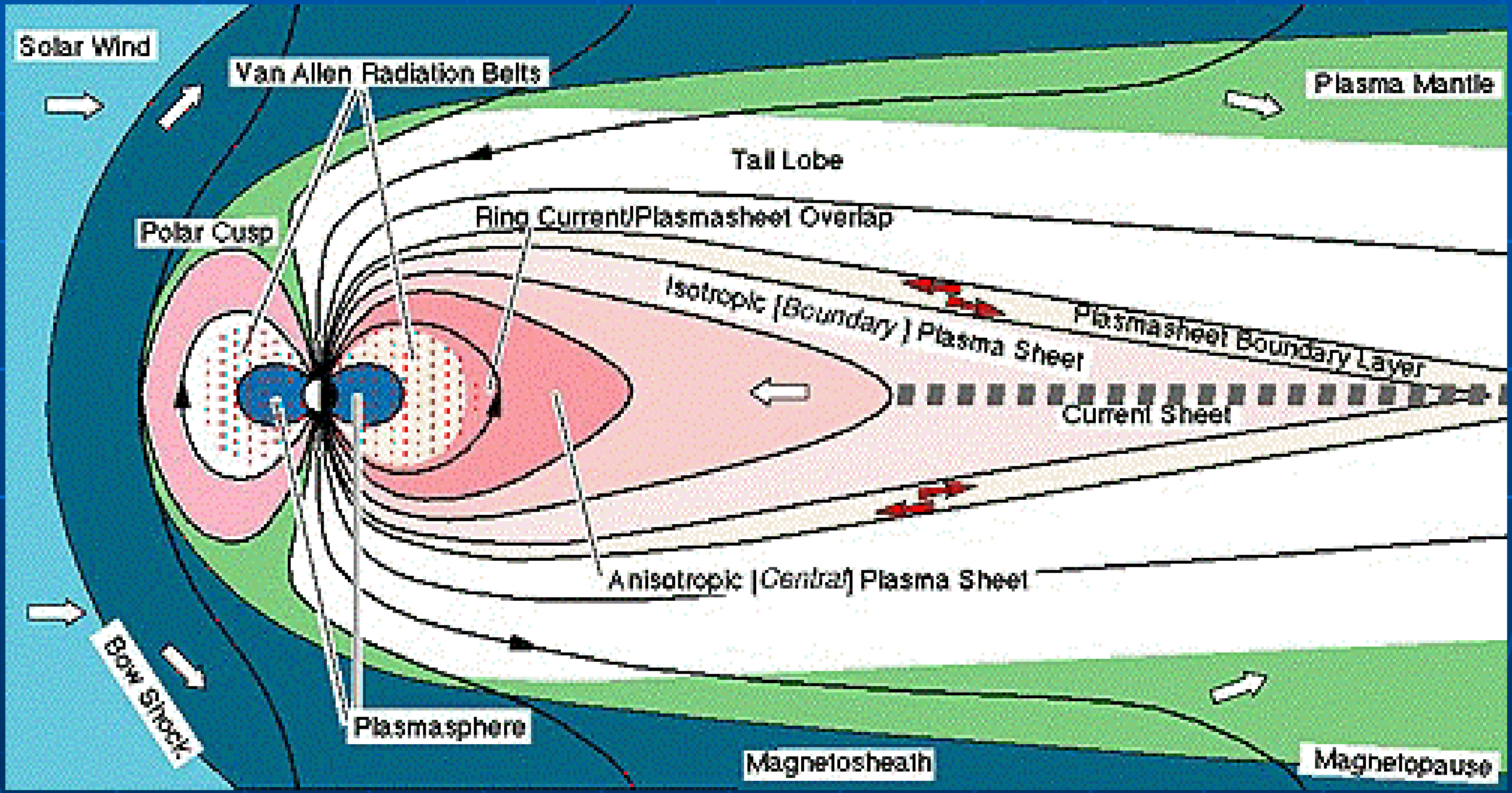
Ionospheric Overview

- Ionosphere: layer of atmosphere (about 300 – 1000 km high) which contains charged particles
- this layer increases the GPS signal delay between satellite and user

  unknown delay creates GPS position error

  density varies daily (max in afternoon; created by solar radiation)

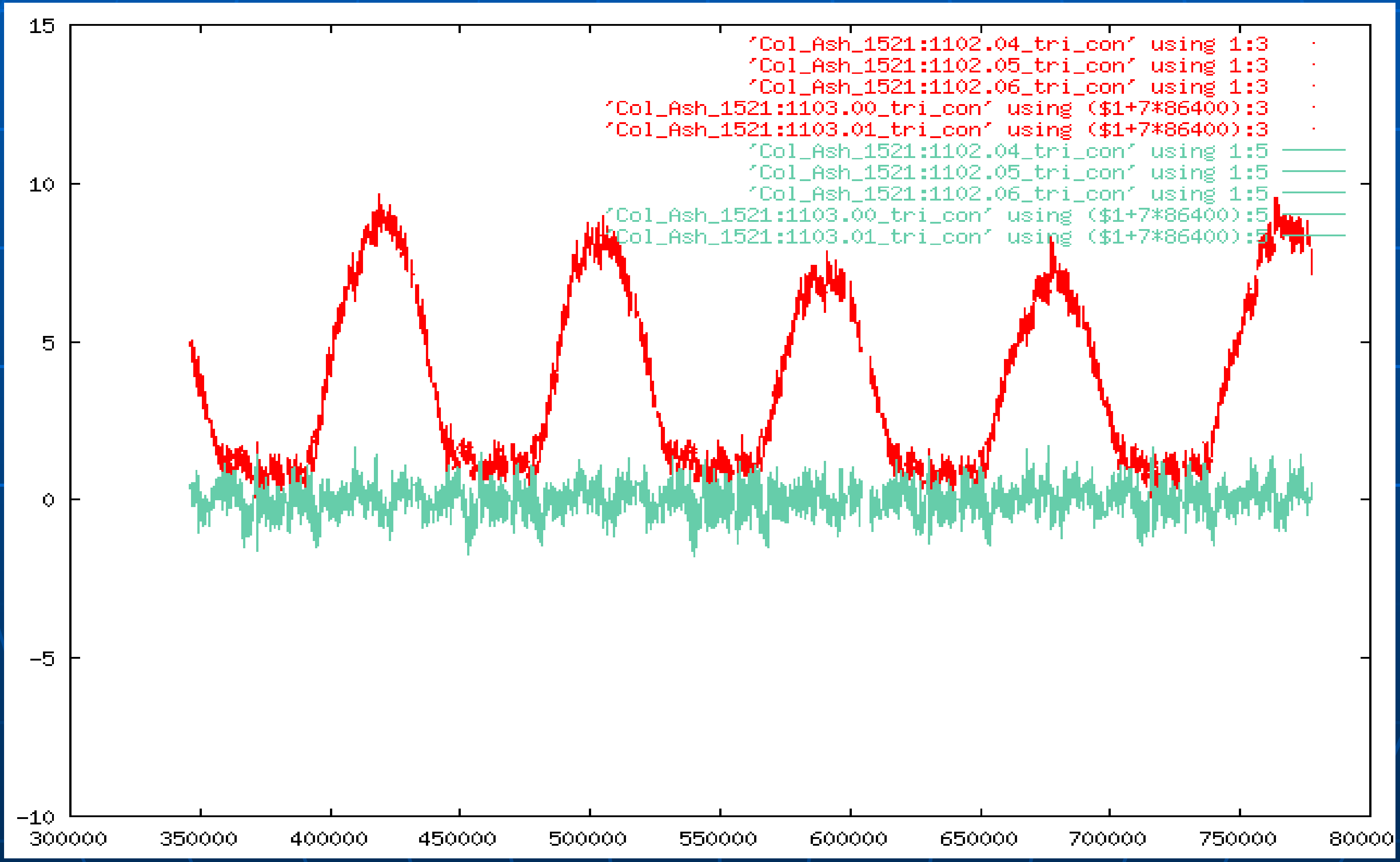
  density also driven as complex part of interaction between the spinning magnet (Earth) and solar wind with varying magnetic fields and cycles
- currently the largest source of GPS Position Error which user frequently experiences



Solar Wind
Van Allen Radiation Belts
Plasma Mantle
Tail Lobe
Ring Current/Plasmasheet Overlap
Polar Cusp
Isotropic [Boundary] Plasma Sheet
Plasmasheet Boundary Layer
Current Sheet
Anisotropic [Central] Plasma Sheet
Bow Shock
Plasmasphere
Magnetosheath
Magnetopause

Example Data – US – Non-storm

(Columbus, Nebraska TRS, 5 days over Weeks 1102-1103)
x axis shows secndsofwek
y axis shows vertical iono delay (red) and irregularity (green) in meters



Ionosphere and GPS

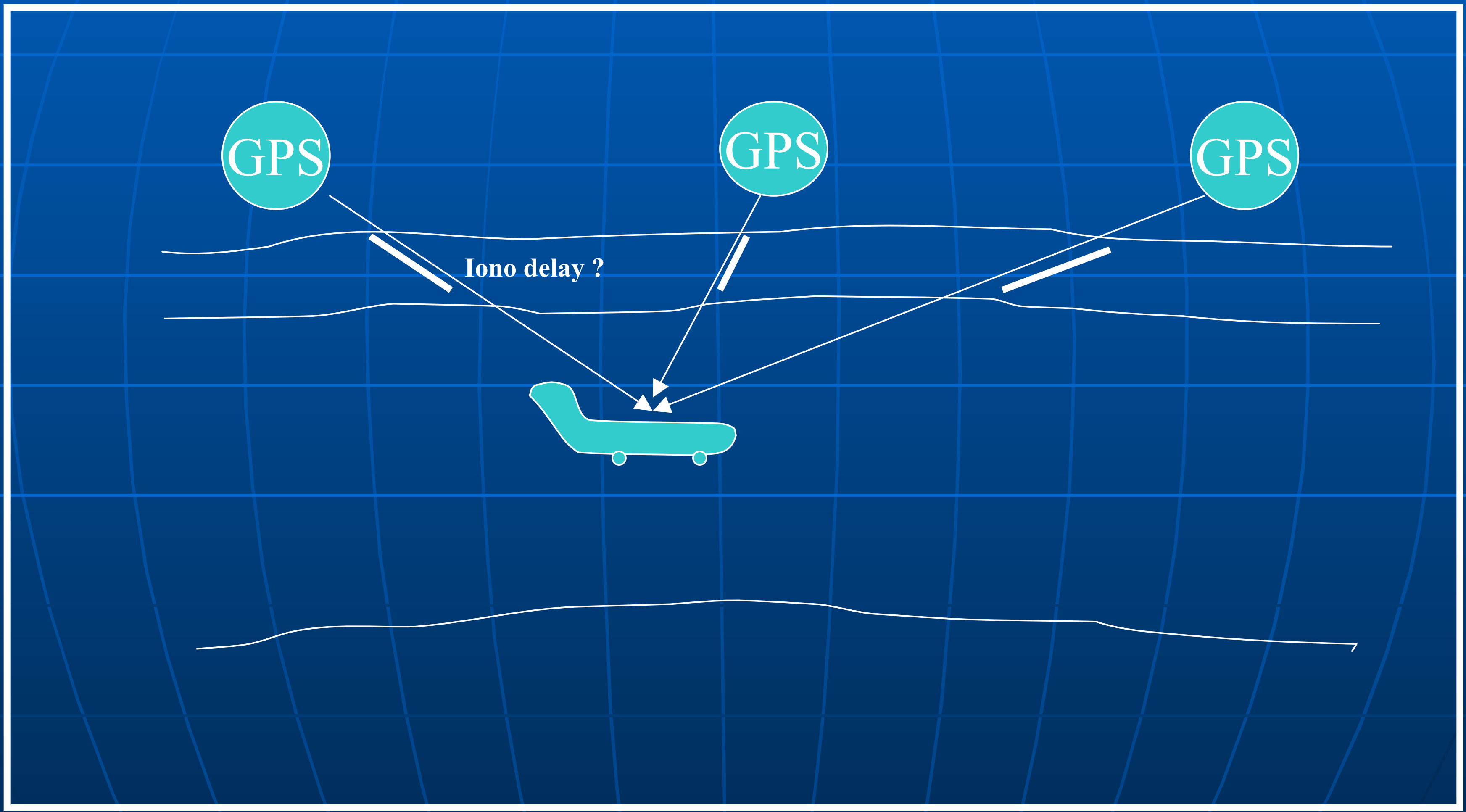
- Iono delay is frequency dependent, so L1/L2 user can *measure* delay to remove it
- L2 is currently coded and in non-protected frequency band, so not intended for use in aircraft safety-of-life operations
- L1-only GPS-SPS user forced to use internal model (Klobuchar model), with coefficients update weekly (or so)
- not accurate or have enough integrity for precision approach users

  (but sufficient for enroute thru Non Precision Approach operations)

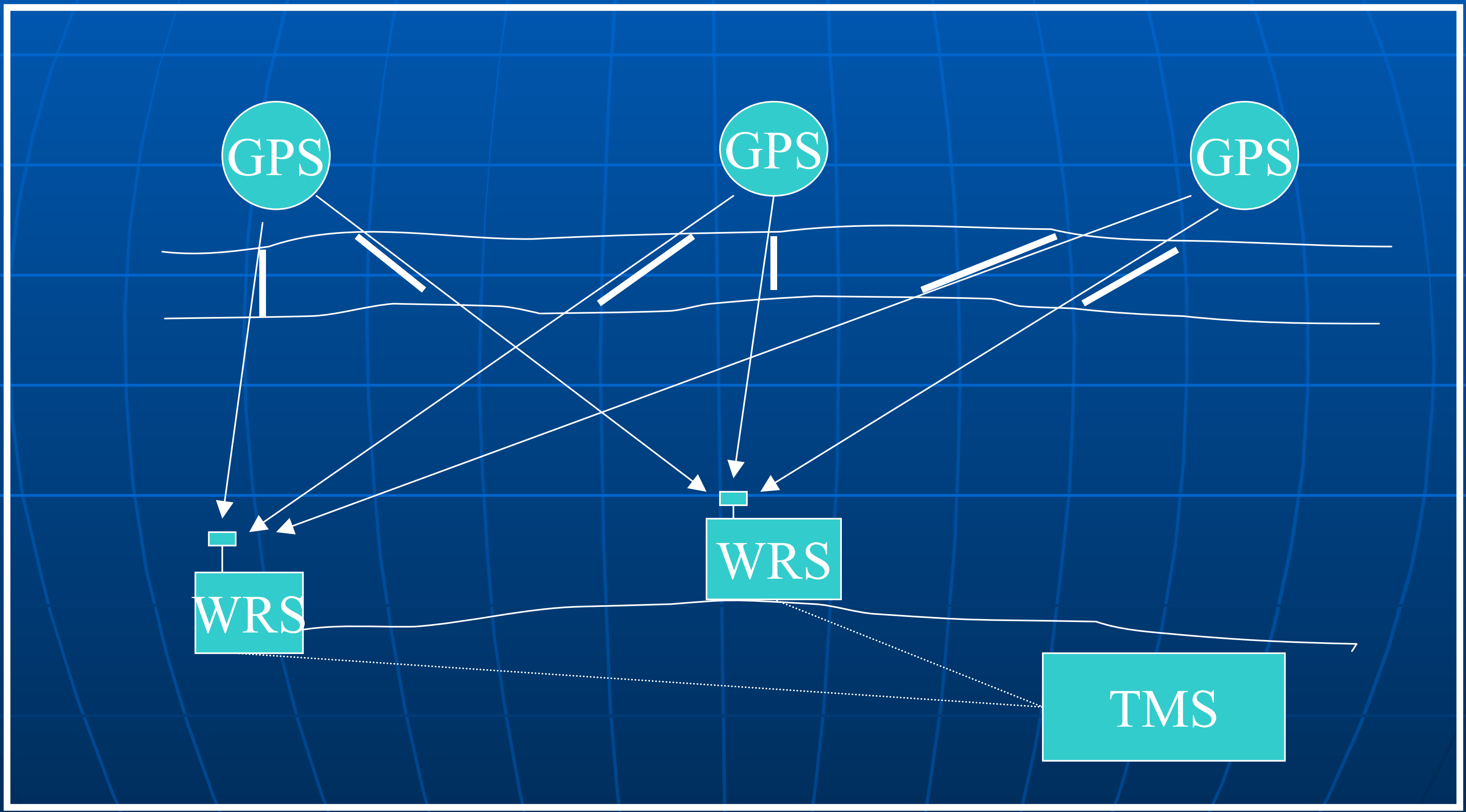
WAAS Ionosphere

- WAAS (for PA or LNAV/VNAV) uses Reference Station L1 and L2 measurements to construct ionospheric grid
- Vertical delay and GIVE at “Iono Grid Points” (every 5 degrees Latitude/Longitude) transmitted to all users at part of WAAS message
- User interpolates iono delay and GIVE for each GPS satellite range
- Interpolated delay used to correct pseudorange
- Interpolated GIVE used as input to VPL equations – and the users guarantee of safety
- GIVEs under 6 meters are generally necessary to support LNAV/VNAV

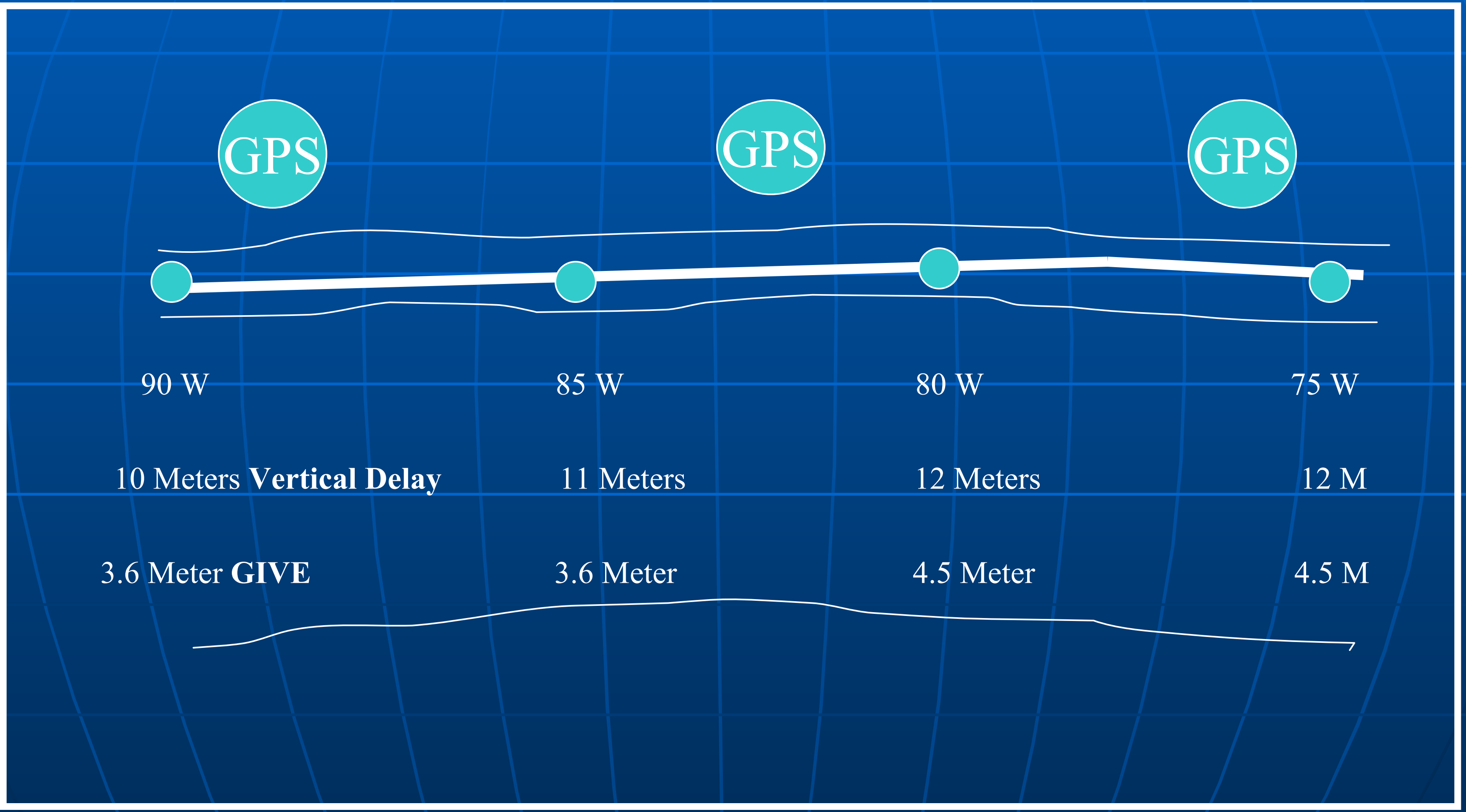
WAAS Ionospheric Grid – A
(Aircraft - 2 dimension example)



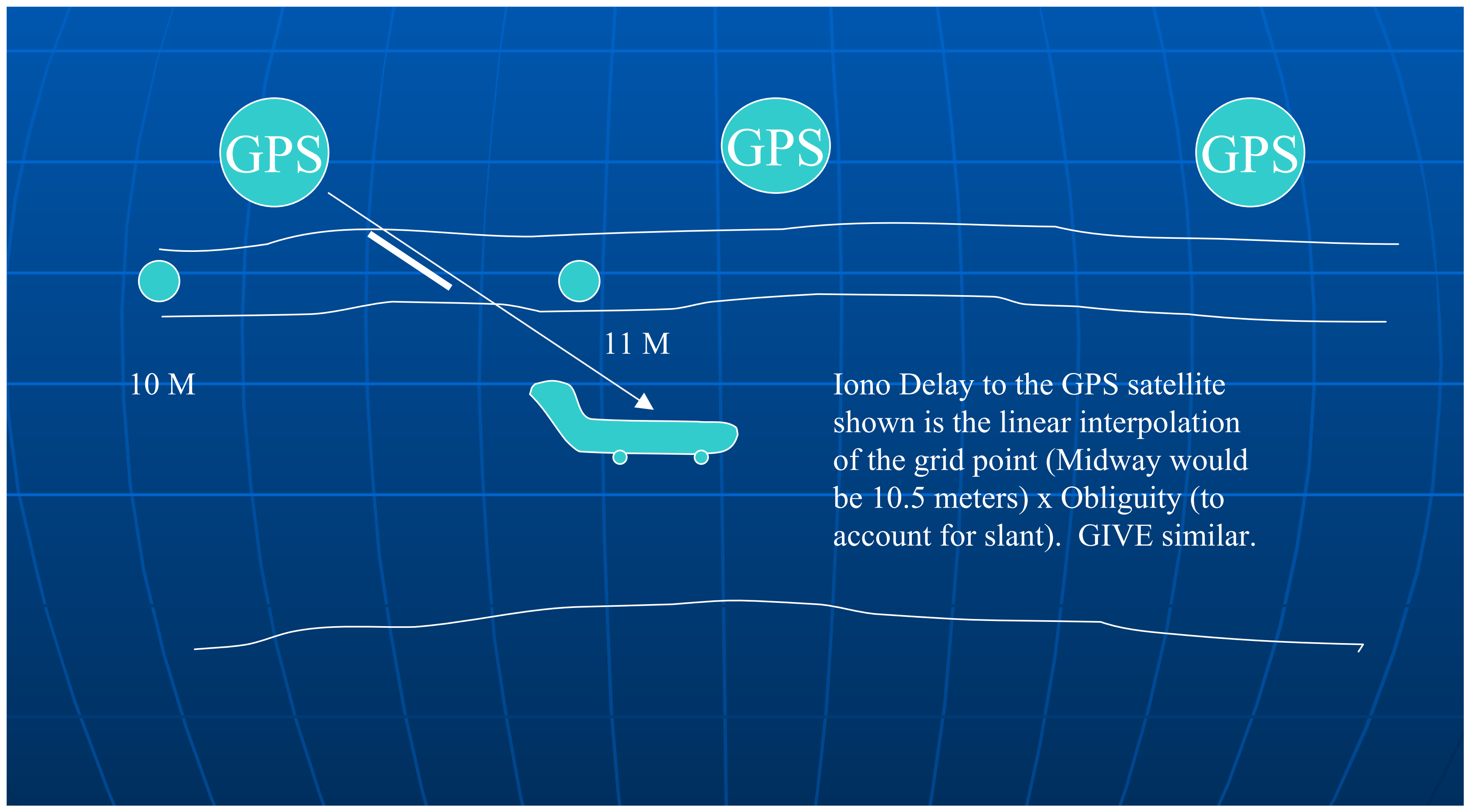
WAAS Ionospheric Grid - B
(2 dimension example)



WAAS Ionospheric Grid - C
(2 dimension example)



WAAS Ionospheric Grid – D (Conclusion)



WAAS Ionosphere II

(How are GIVEs accepted to be safe)

WAAS safety-approved GIVE algorithm based on normally, very flat (planar) ionosphere over CONUS (1 sigma, 35 cm!)

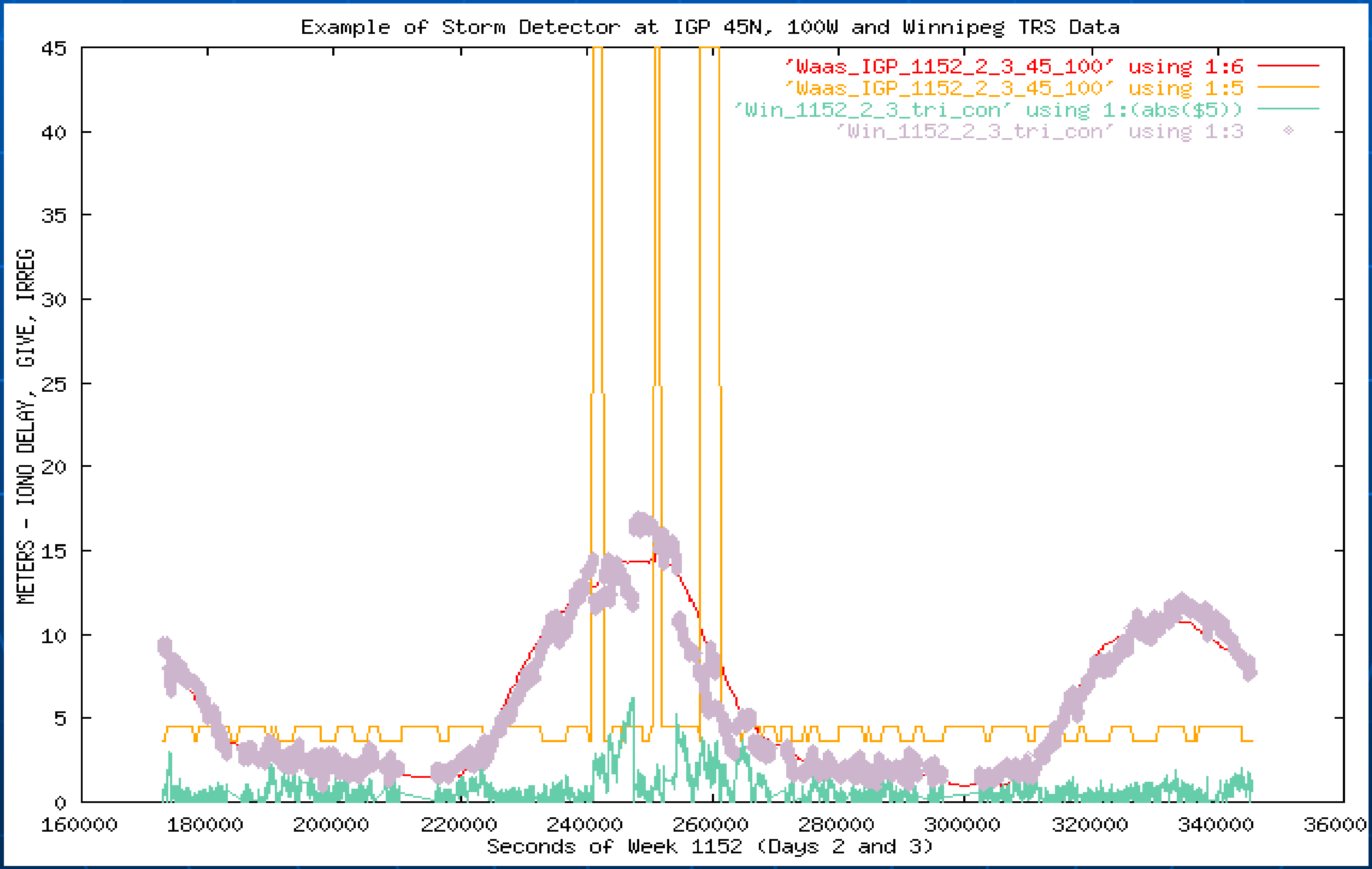
- Flat, planar ionospheric delay allows accurate interpolation from Iono Grid Points (spaced 5 degrees apart)
- Iono experts and safety expert panel (WIPP) agreed that:
  - No large irregularities except during iono storms
  - Storms can be safely detected as irregularities by "storm detector"
  - GIVEs can be safely increased to 45 meters during storms
  - Because iono measurements are spread out over the ionosphere, non-storm conditions were analyzed to determine largest, normal threat that could still be in ionosphere and escape detection – this is the undetected threat model – the max is about 2 meters.
  - Undetected threat model is always added to GIVEs to guarantee safety

WAAS Ionosphere III

- National Satellite TestBed (NSTB) Data example
  - Vertical delay determined for Ionospheric Grid Point near Columbus, Nebraska, Reference Station, using nearest IPP
  - Estimate of local uncertainty developed by performing planar fit of three surrounding IPPs;
  - Irregularity response to geomagnetic storm apparent ~ 6 m
  - WAAS Data shows similar iono vertical delay, and shows response to geomagnetic storm (GIVEs jump to 45 meters)
  - WAAS iono monitoring and safety case was a major reason for
    WAAS program delay

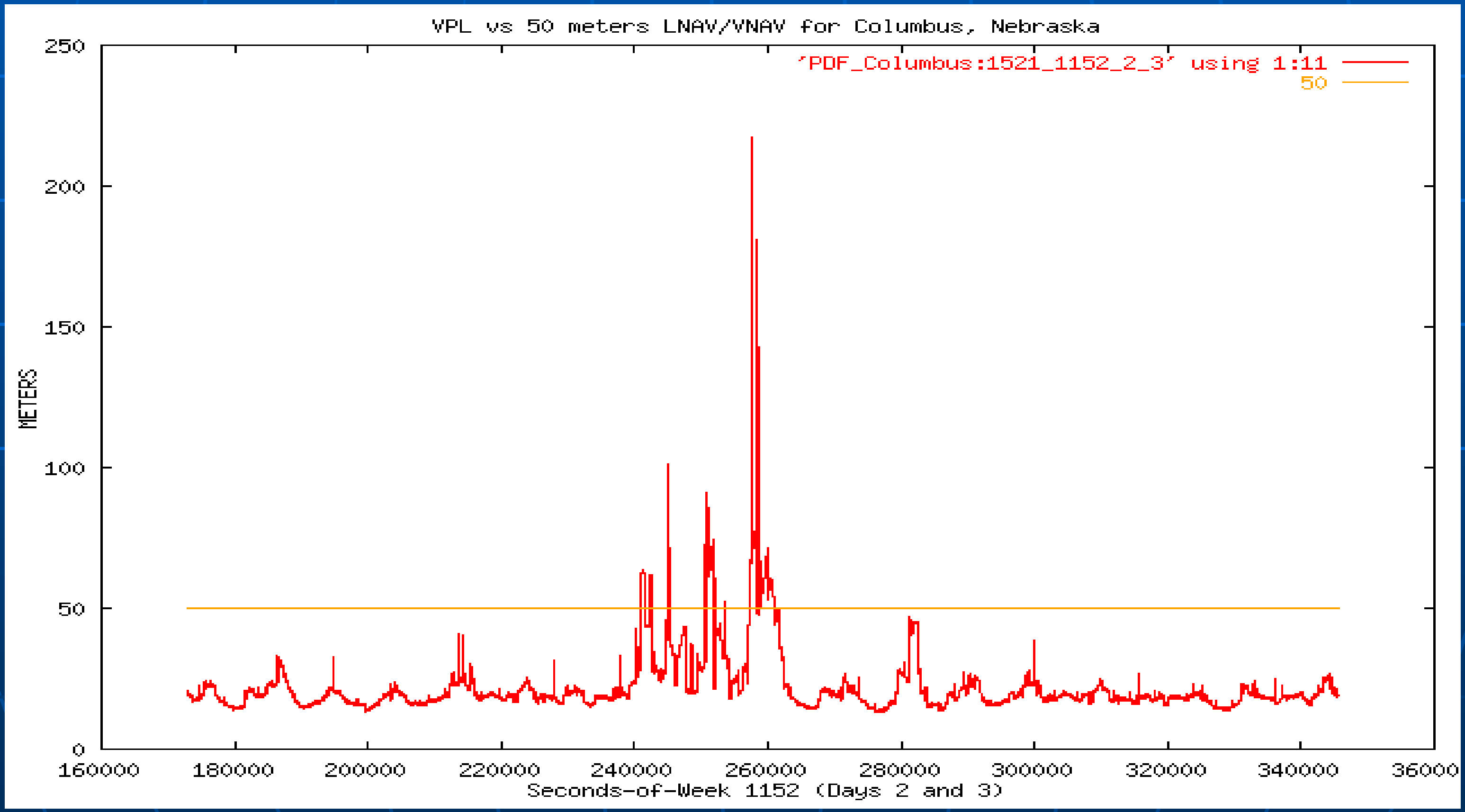
WAAS Ionosphere

Example 1 – IGP and Iono Irregularity – Iono Storm response



WAAS Ionosphere

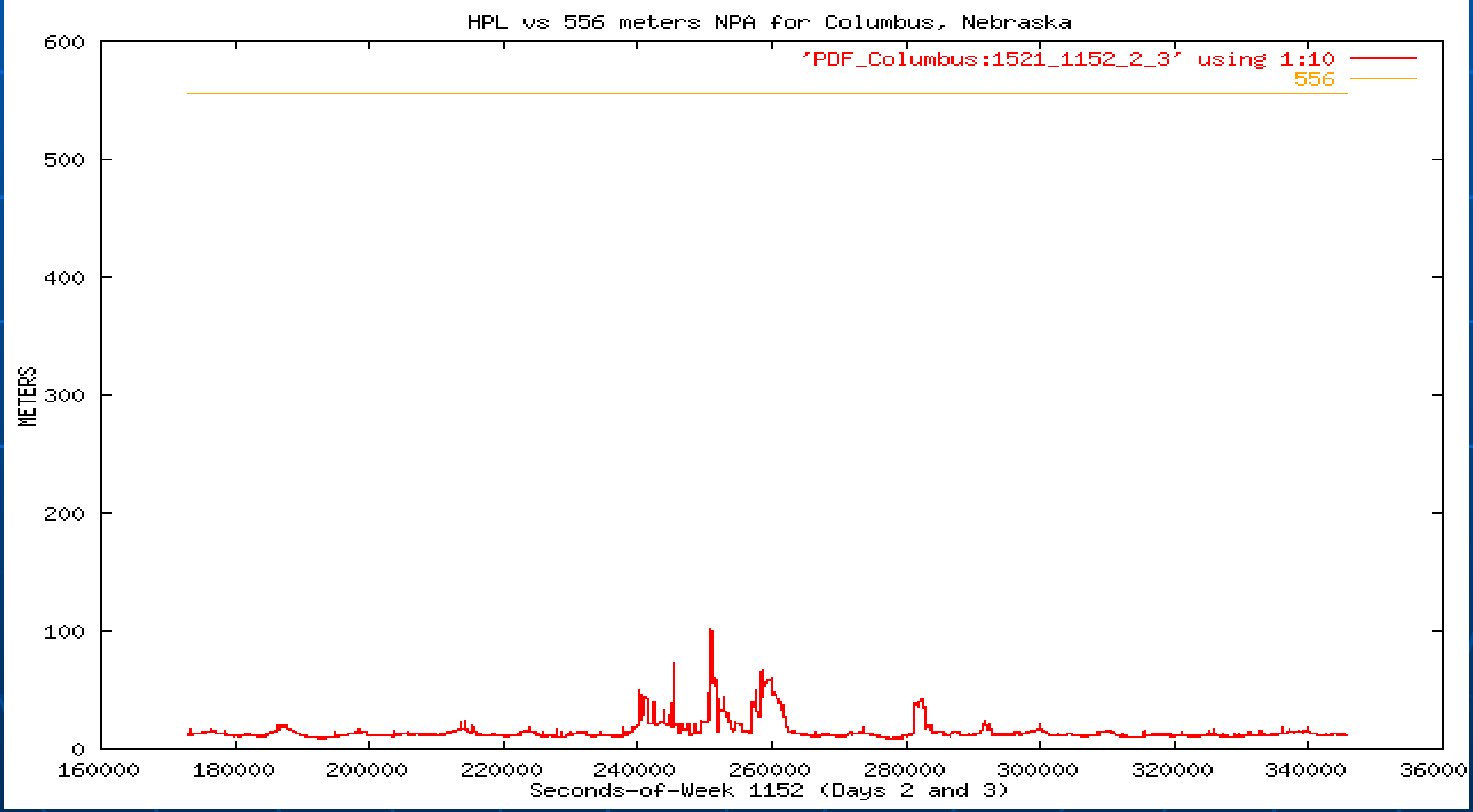
Example 2 – VPL for LNAV/VNAV Storm Impacts Availability



WAAS Ionosphere

Example 2 – HPL for NPA

Storm has no impact on NPA Availability

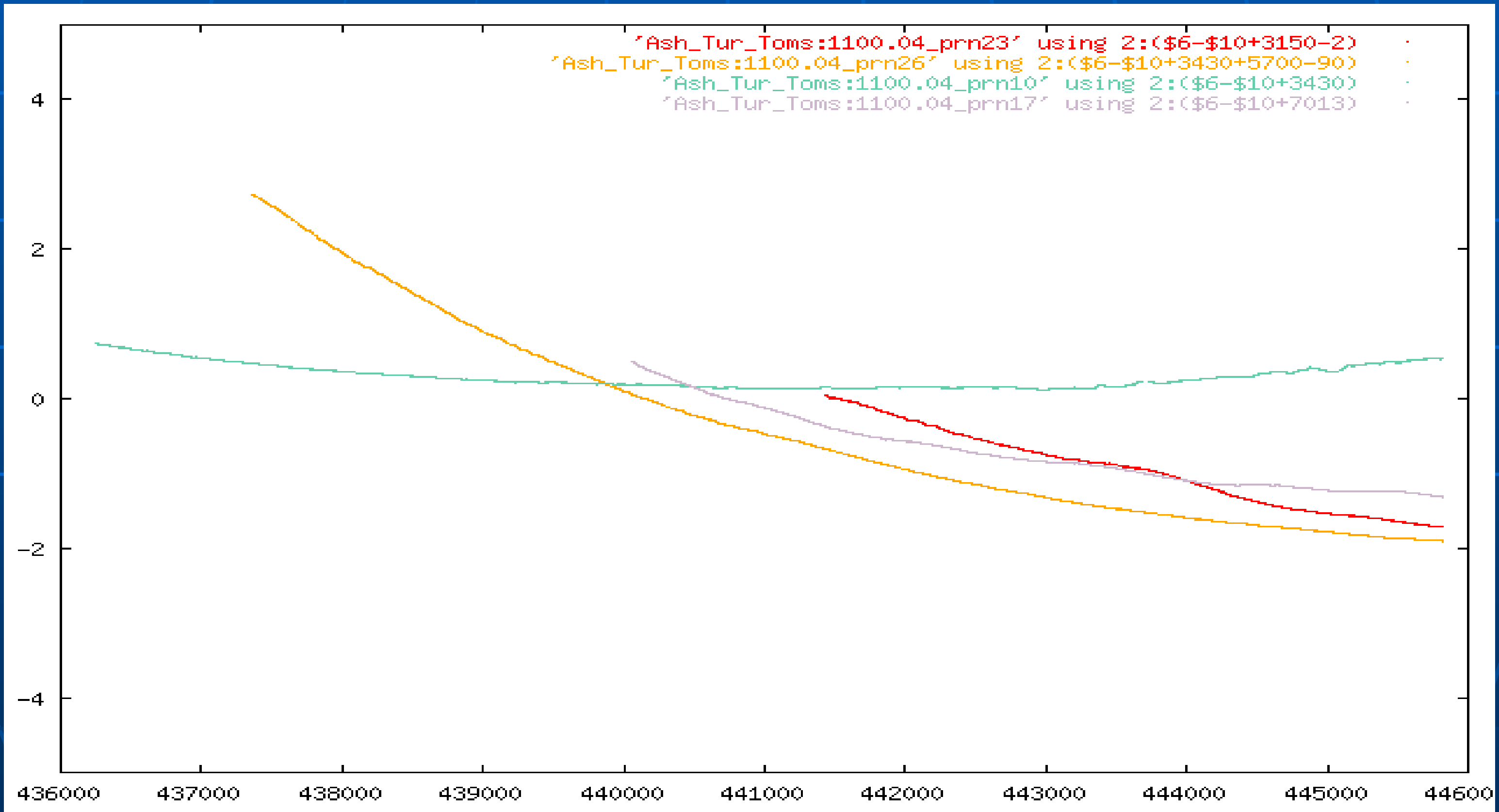


Geomagnetic Equator
Initial NSTB Observations 1999-2000

Example Data – US – Non-storm

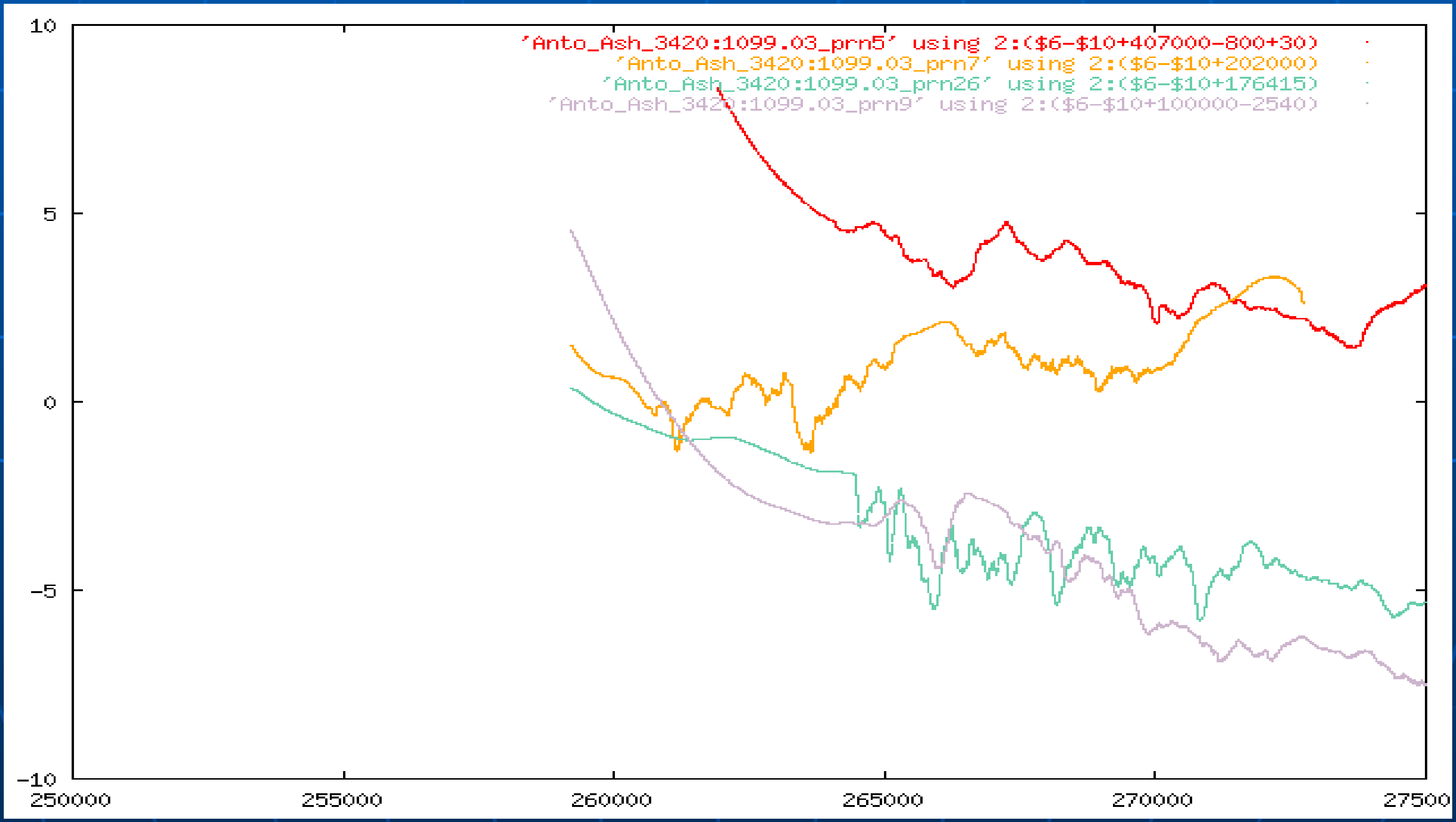
~3 hour GPS carrier-carrier

(change in value due to slow iono change and obliquity)



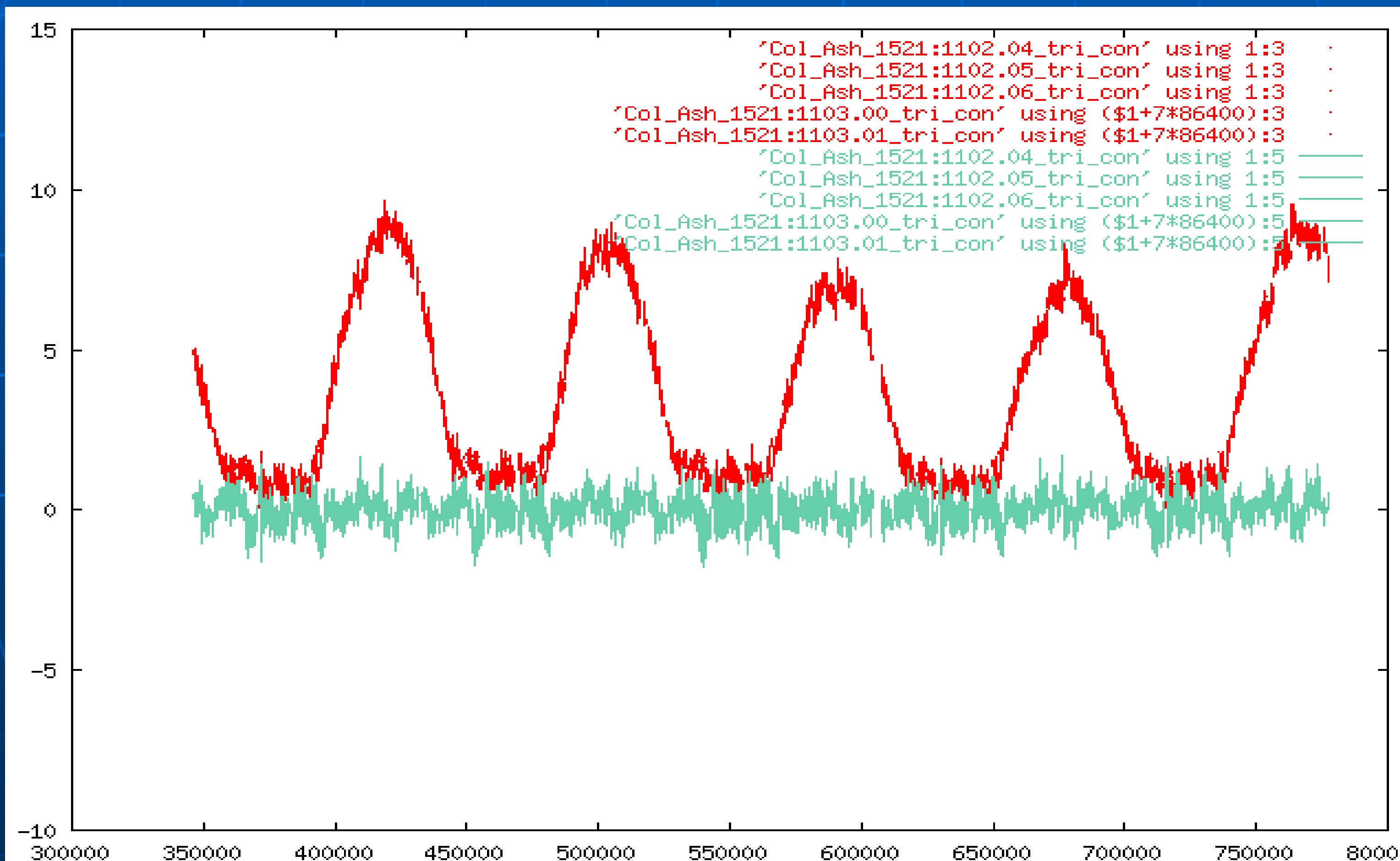
Example Data – Antofagasta, Chile

Non-storm but affected by equatorial anomaly
~4 1/2 hour GPS carrier-carrier
(change in value due to iono change and obliquity)
x axis shows seconds of week 1099 and y axis shows meters



Example Data – US – Non-storm

(Columbus, Nebraska TRS, 5 days over Weeks 1102-1103)
x axis shows secndsofwek
y axis shows vertical iono delay (red) and irregularity (green) in meters

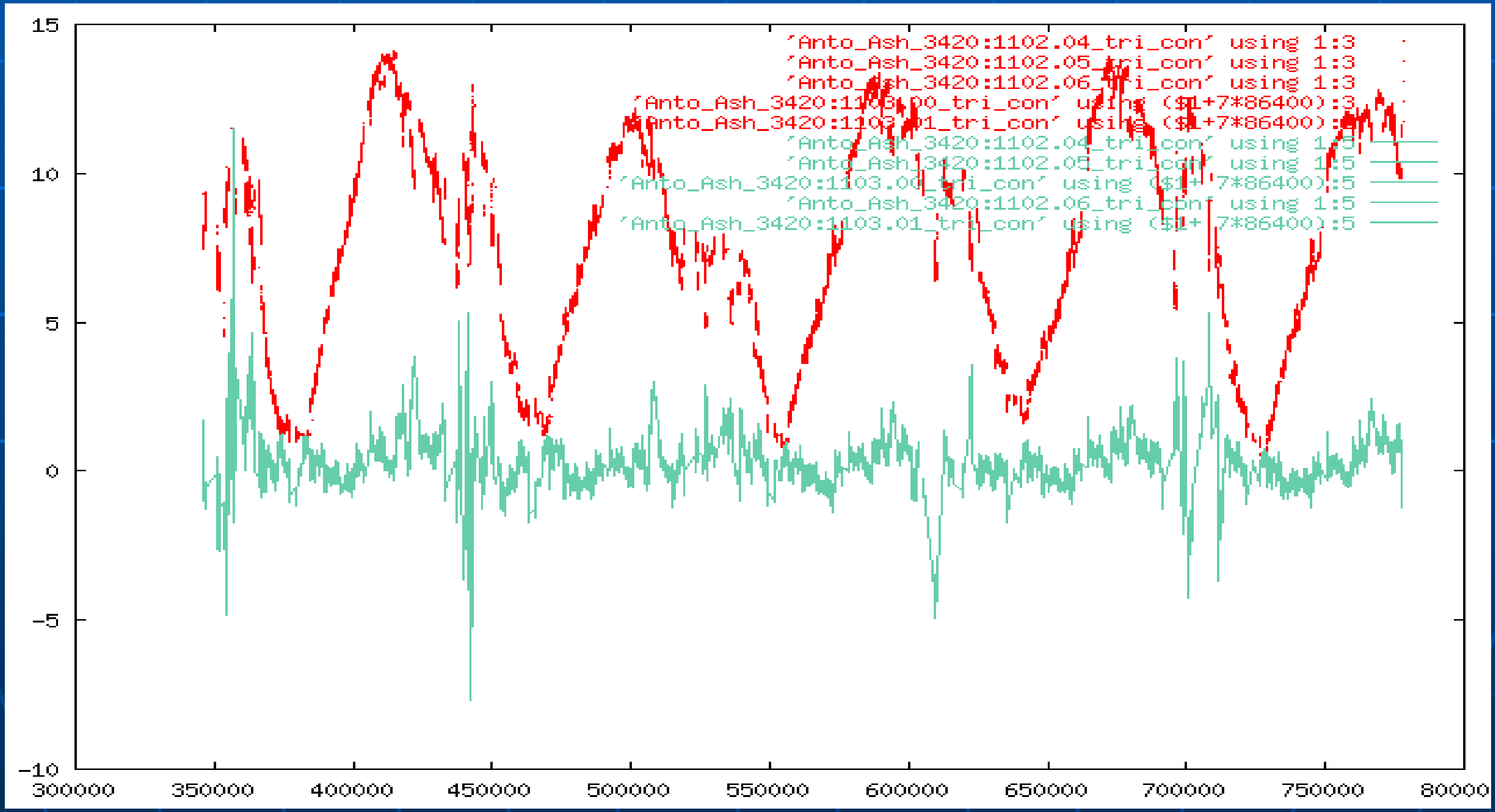


Example Data – Antofagasta, Chile

Non-storm but affected by equatorial anomaly

~5 days showing verticl iono delay (red) and irregularity (green) with simple planar method

x axis shows seconds of week 1102 into 1103 and y axis shows meters



Ionosphere – US vs. Geomagnetic Equator

- Ionospheric delay over CONUS usually very smooth
  - 1 sigma deviation from plane of 35 cm of 2000+ km
  - Exceptions are during severe geomagnetic storms

- Geomagnetic equator has significant anomaly
  - Caused by drift of charged particles in mag. field lines
  - Causes two crests North and South of Geom. Equator

  - Evening events contain "bubbles" and scintillation
  - Scintillation has been studied for many years
  - Effect of anomaly, bubbles and scintillation on SBAS under study

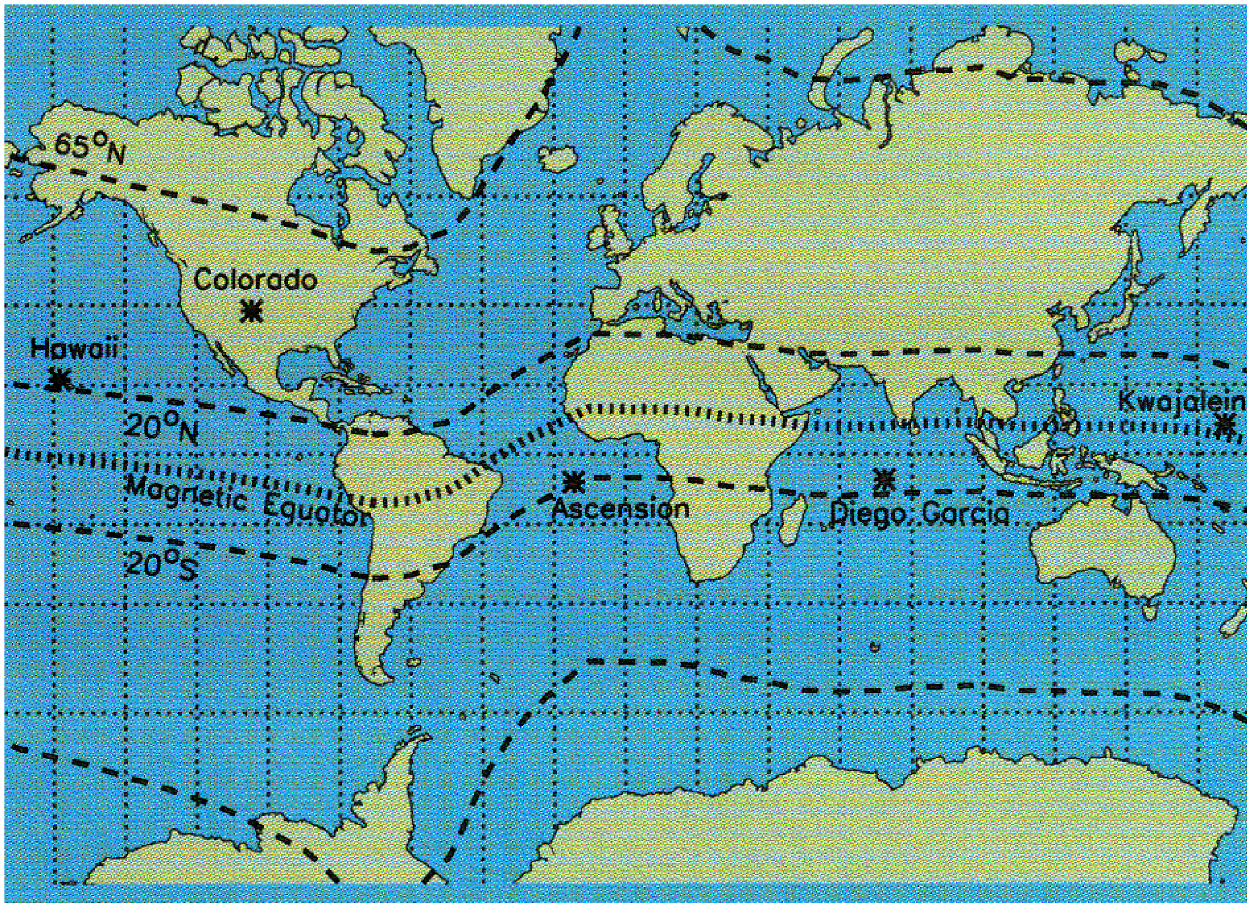
Regions of Scintillation Activity

Low latitudes: strongest effects, limited to post-sunset and pre-midnight, seasonally dependent, not correlated with magnetic activity

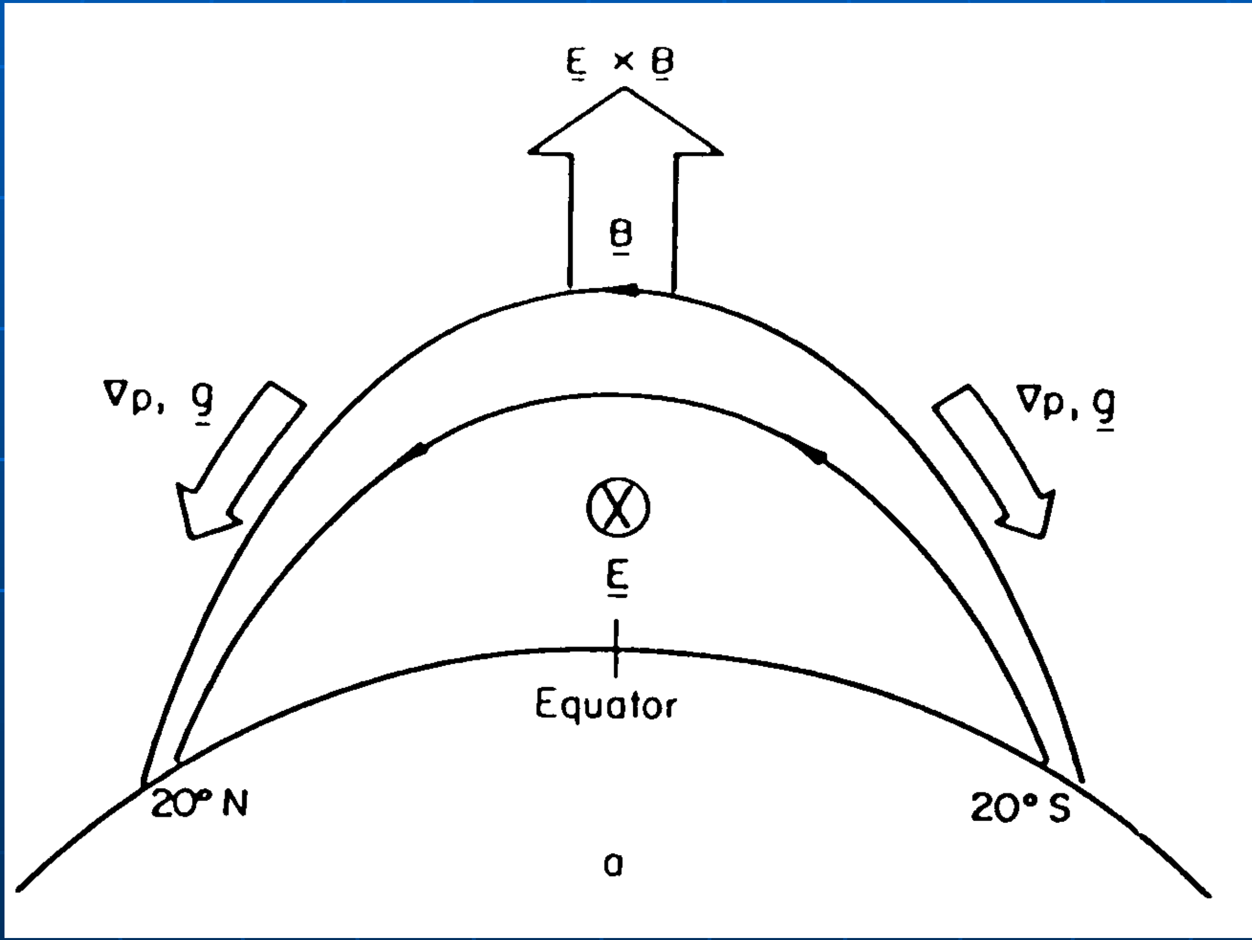
Mid-Latitudes: rare, only during extreme levels of geomagnetic activity

High latitudes: related to geomagnetic activity, less intense than low latitude effects

More intense and frequent during high solar activity in all regions.

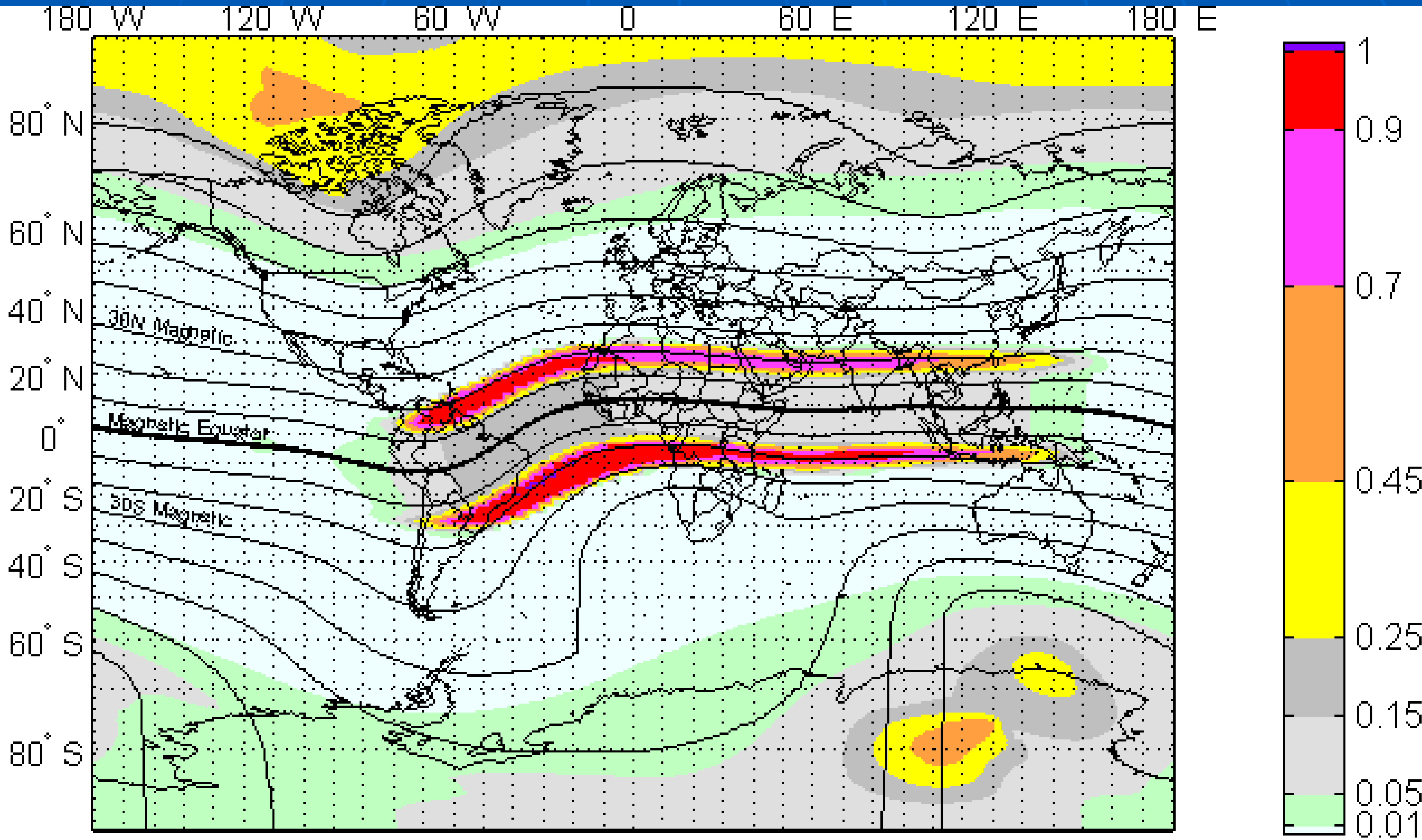


What causes the equatorial anomaly effect?

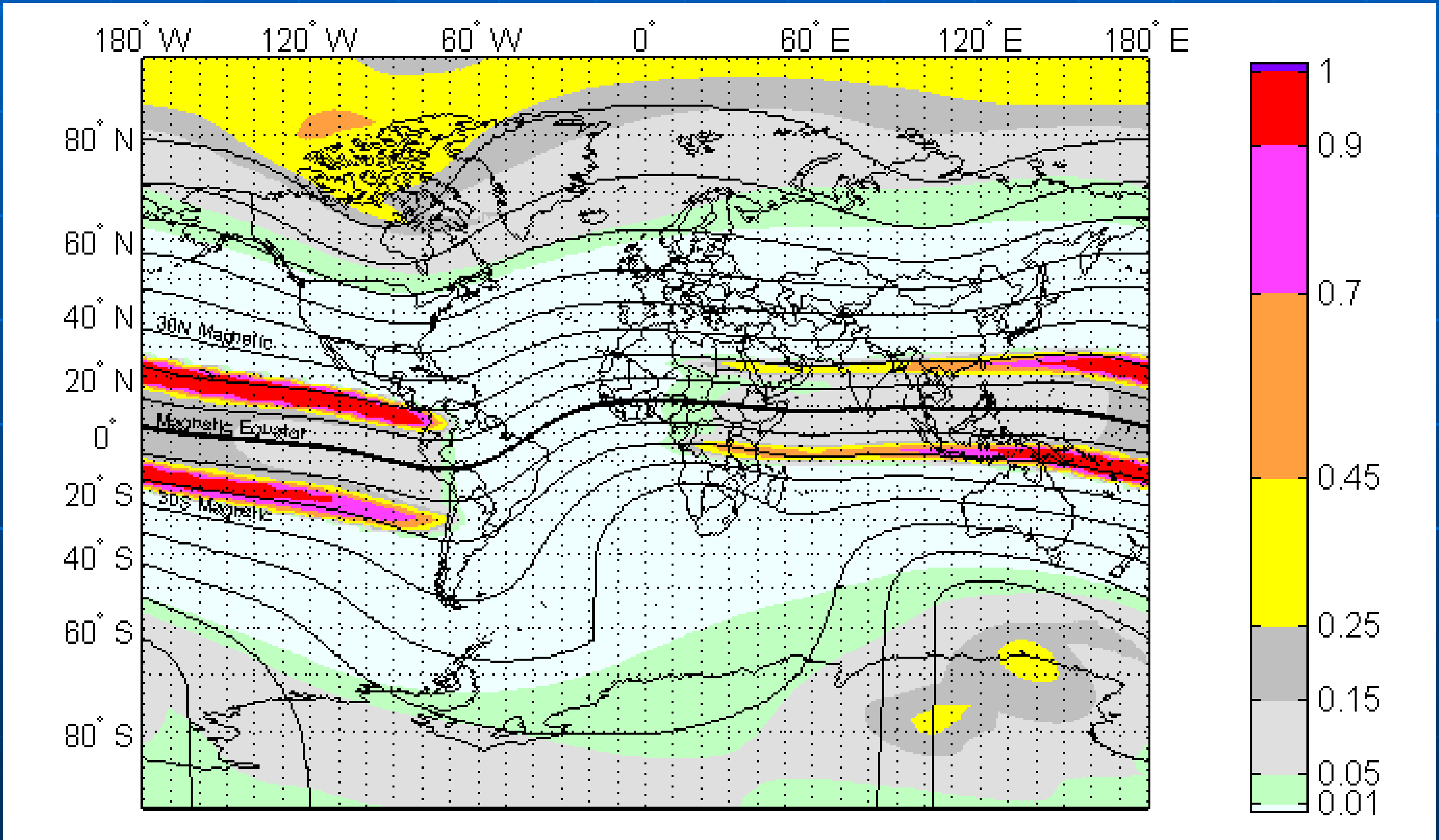


From ":The Earth's Ionosphere", M.C. Kelley, 1989.

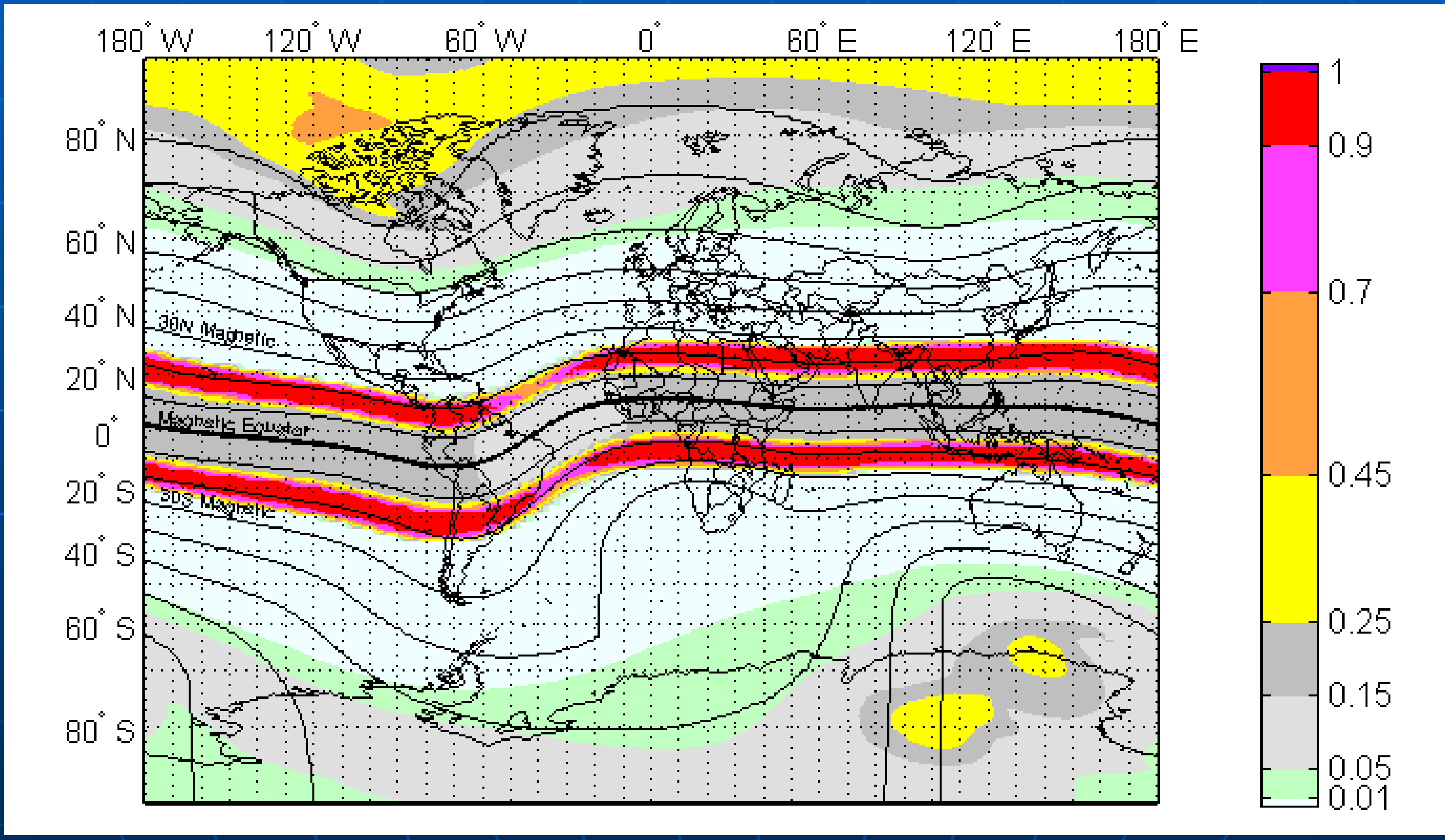
WBMOD Model
S4, January 15, SSN = 150, Kp =1, Local Time = 2100



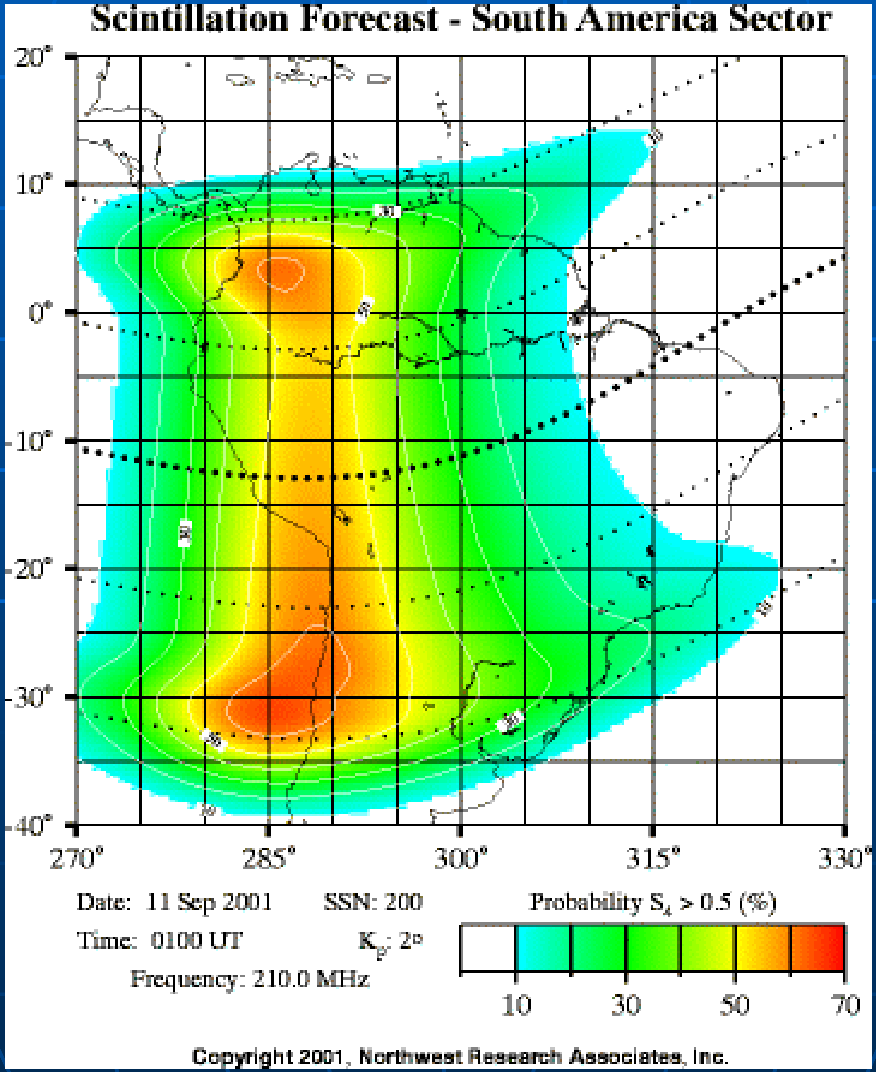
WBMOD Model
S4, July 15, SSN = 150, Kp =1, Local Time = 2100



WBMOD Model
S4, September 15, SSN = 150, Kp =1, Local Time = 2100



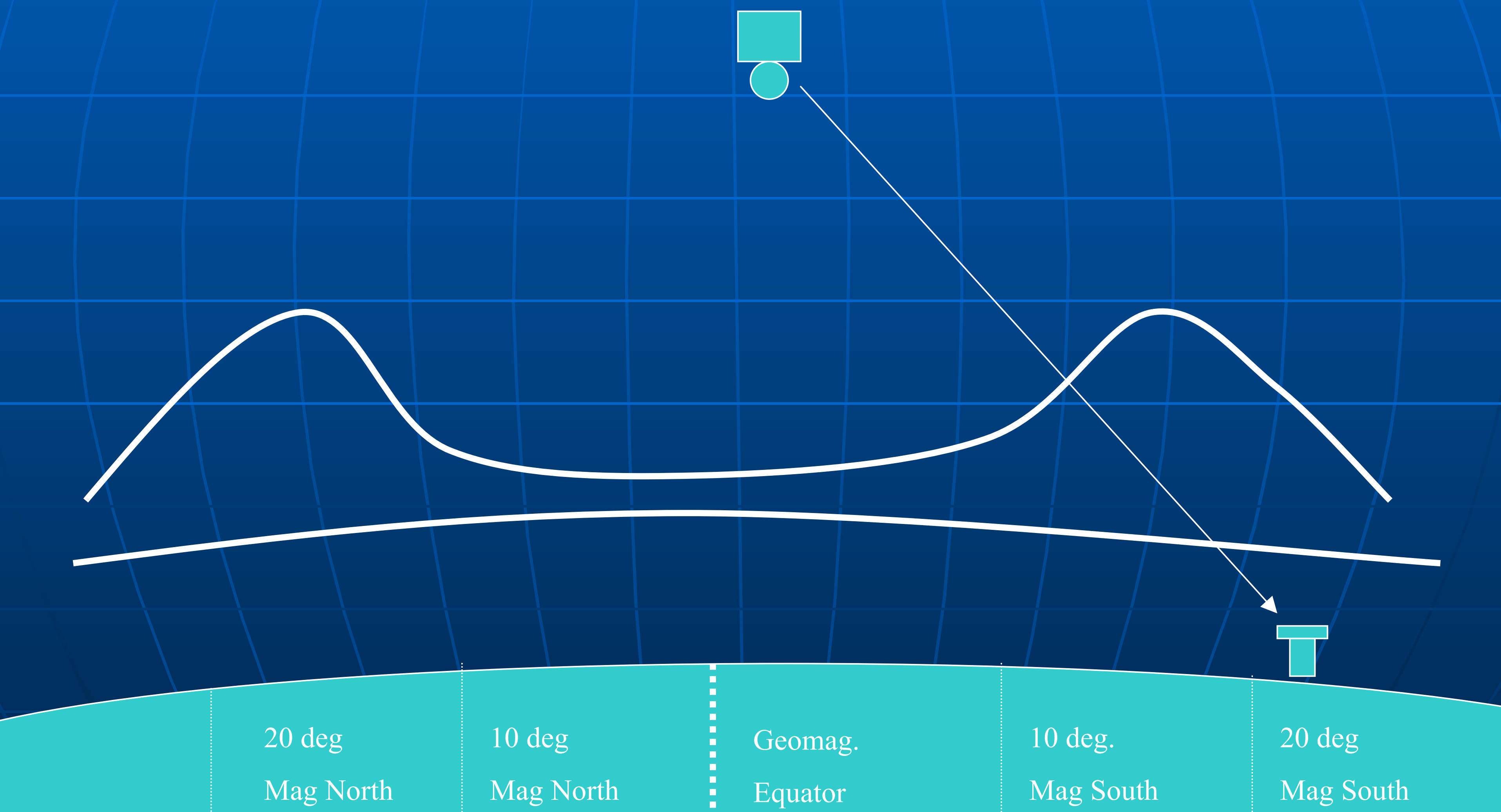
Risks to Planar Ionosphere - III



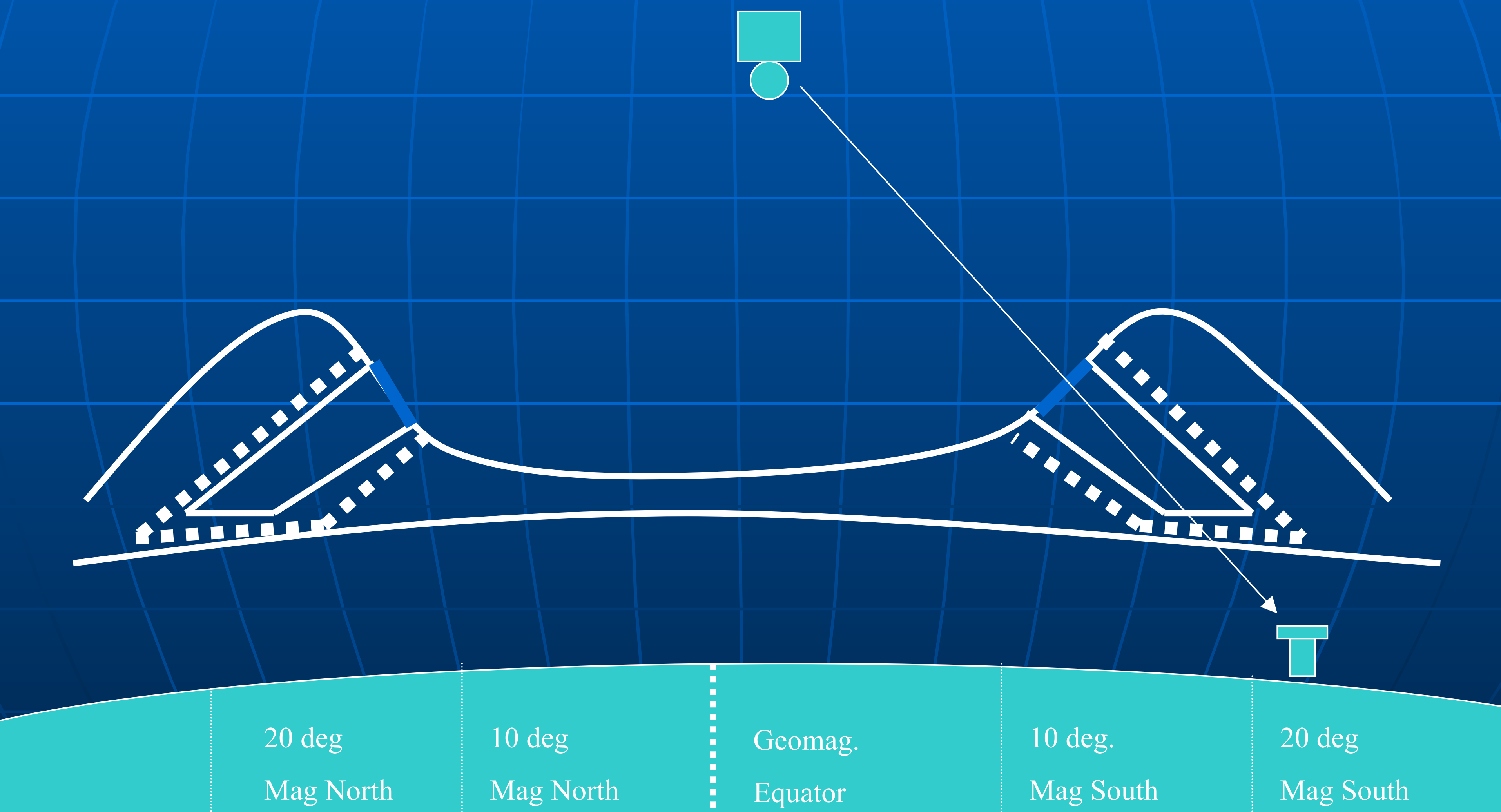
Even worse than the Appleton Anomaly?

- Bubbles
- aka Plasma Depletions
- aka Voids

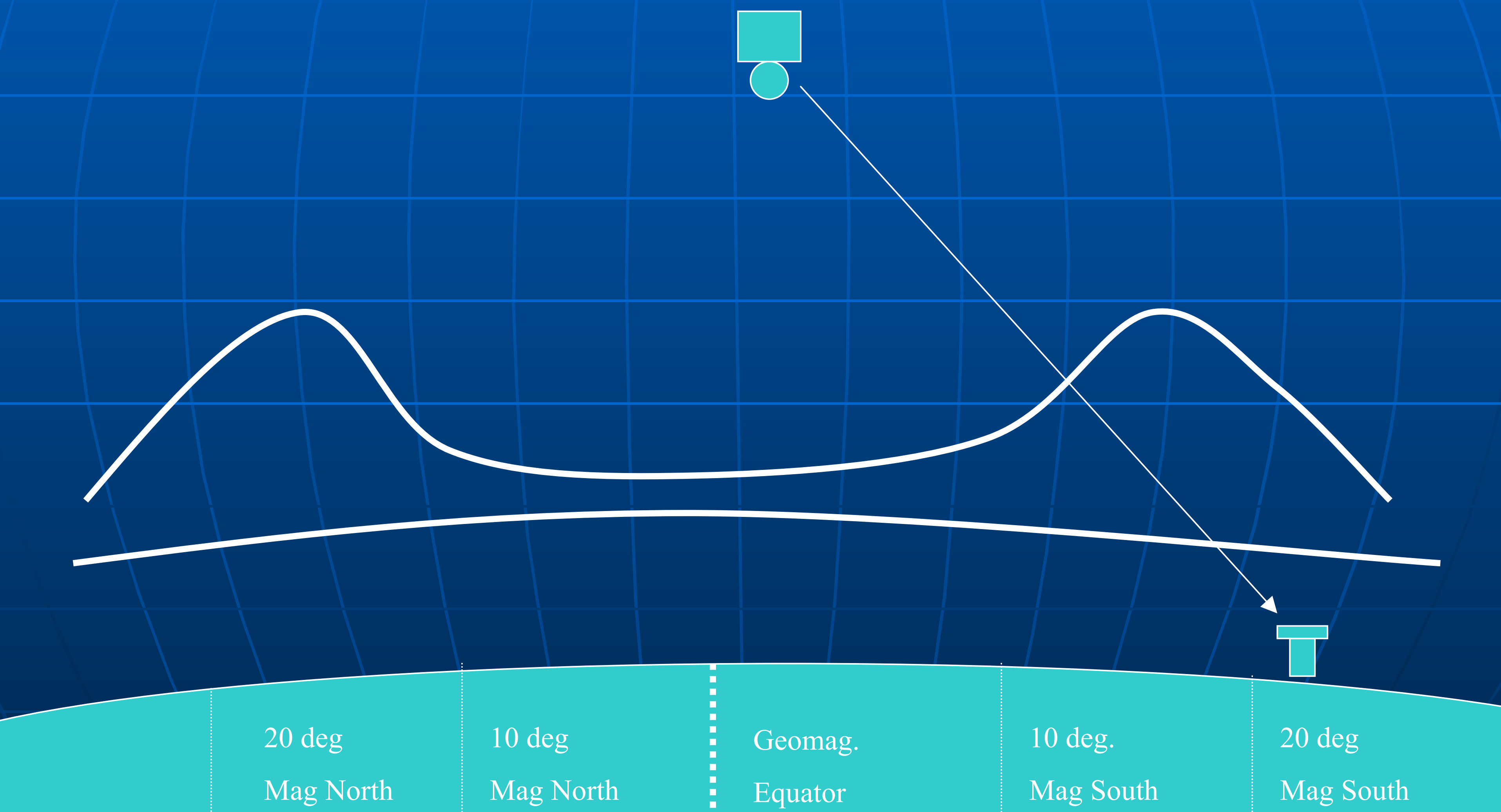
Data Collection Example (time 0, no bubble is line-of-sight)



Data Collection Example
(time 1, with Bubbles/Scintillation in LOS)

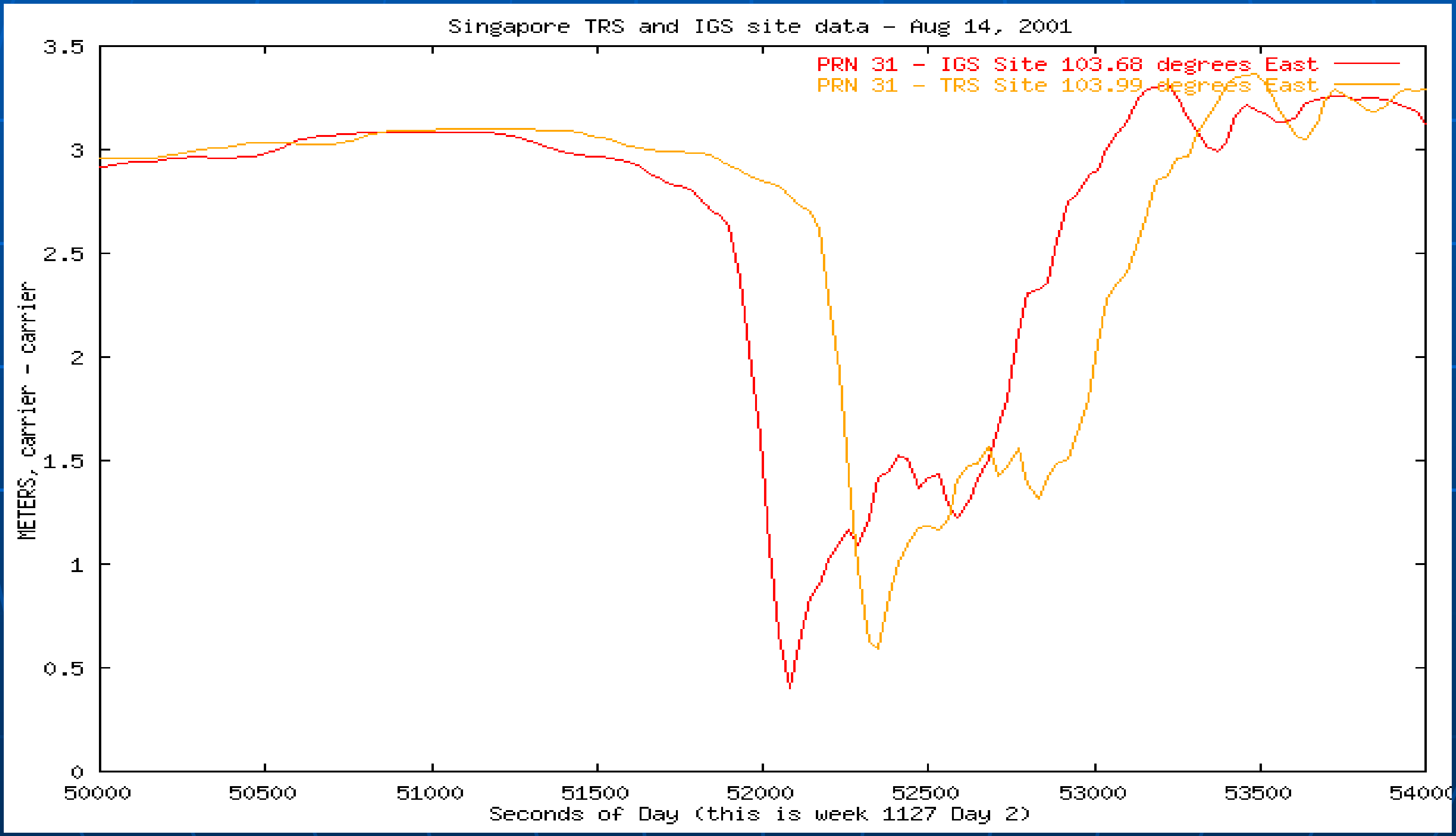


Data Collection Example
(time 3, bubble gone from line-of-sight)
(Bubble moving east > 100 meters/sec)



Risks to Planar Ionosphere

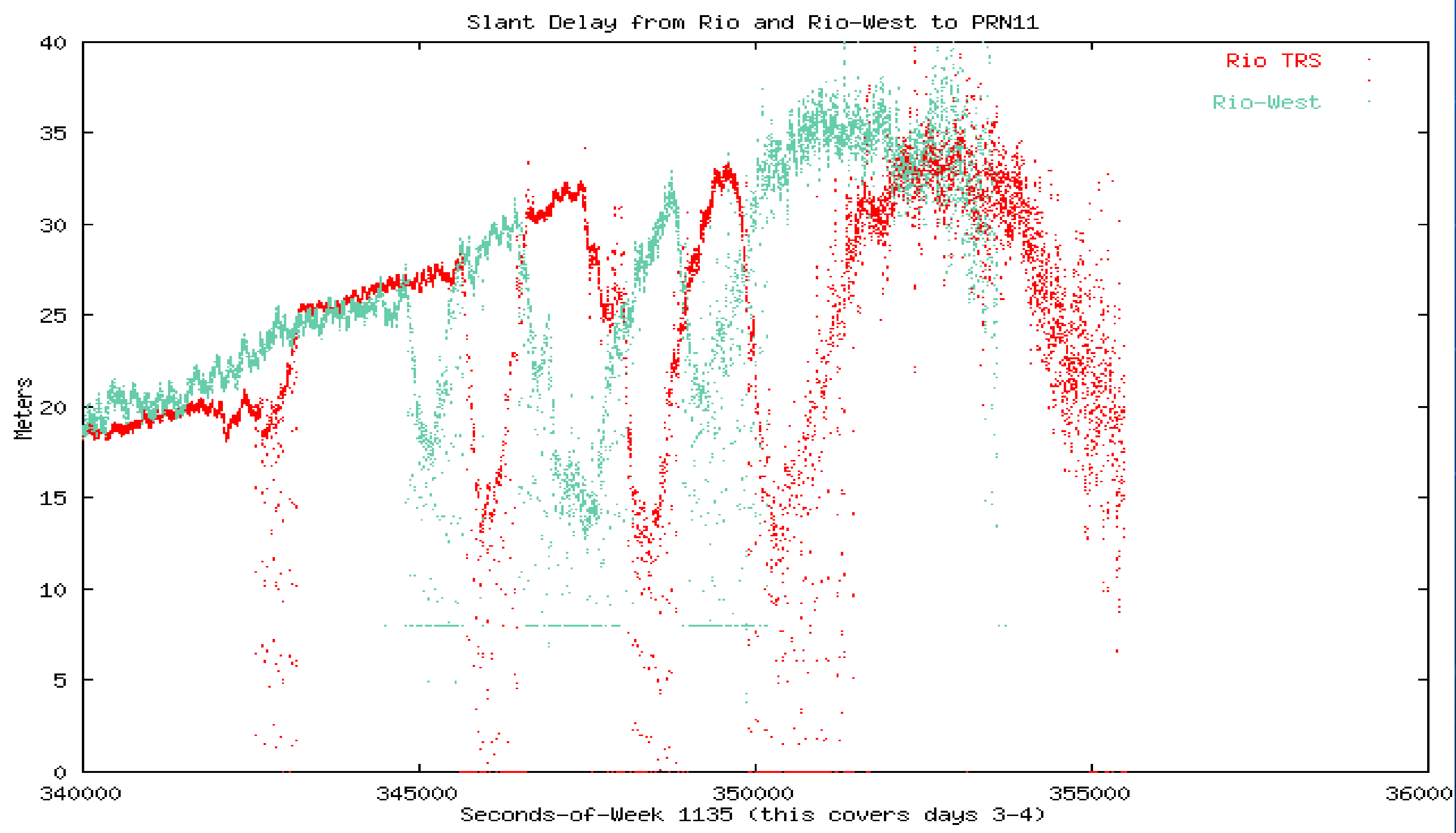
Data from Singapore showing motion in “bubbles’



Risks to Planar Ionosphere

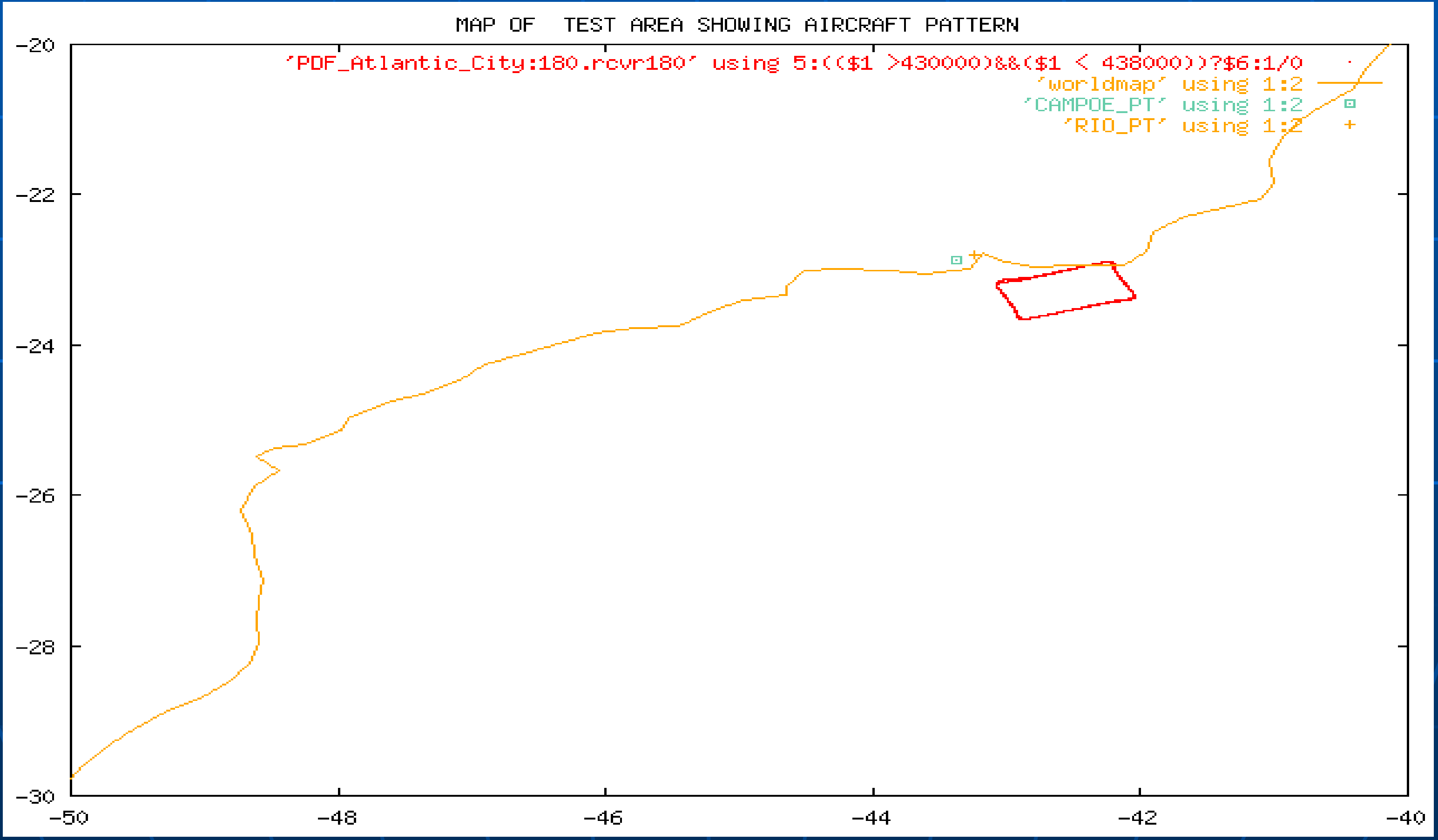
Data from Brazil showing motion in “bubbles’

(Rio-west was a temporary site ~95 km west of Rio TRS)



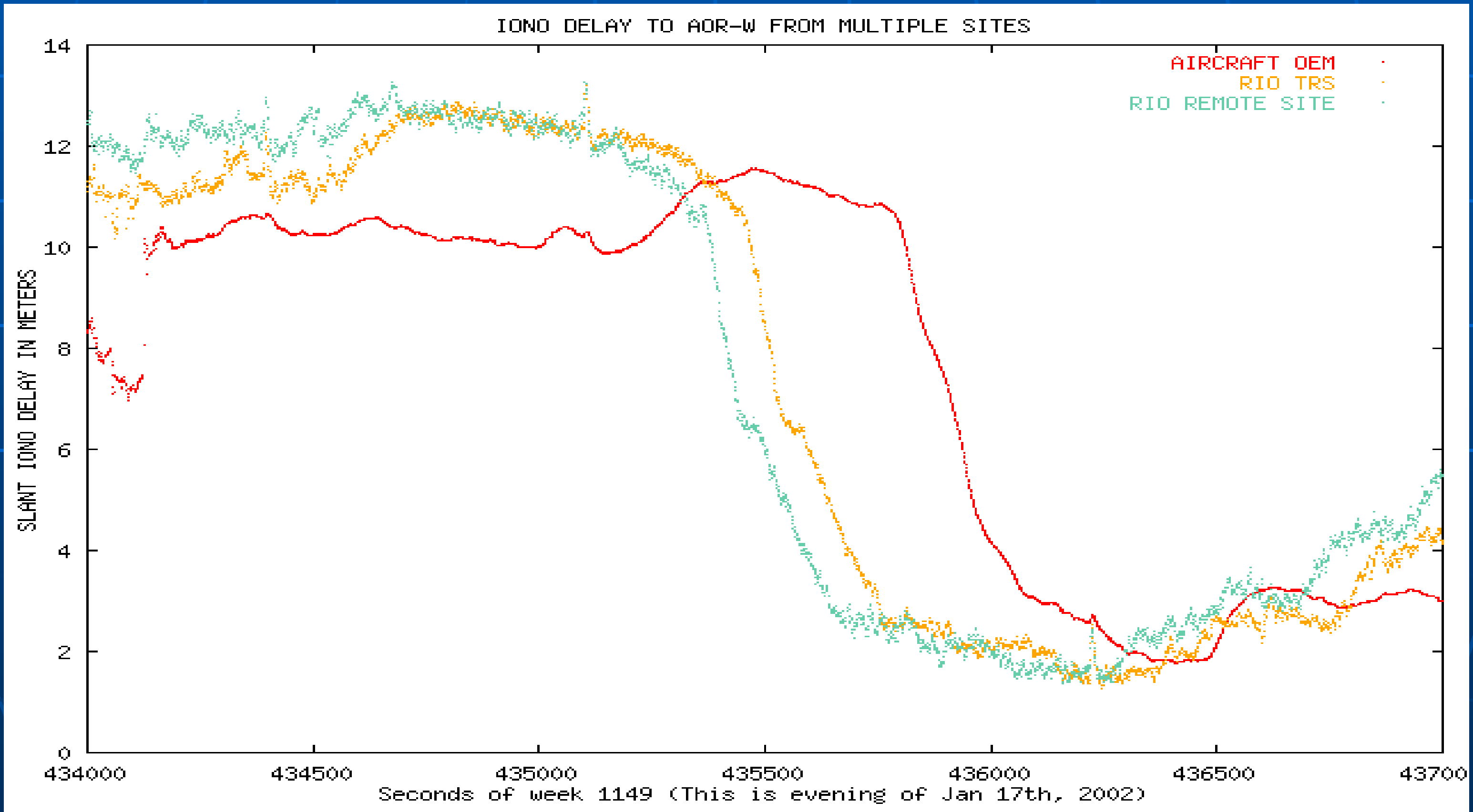
Risks to Planar Ionosphere

(Plots shows location of 2 ground receivers 15 km apart in Rio de Janeiro area, , and aircraft receiver)



Risks to Planar Ionosphere

(Plots shows motion of bubble wall passing 2 ground receivers 15 km apart, then aircraft receiver)



Risks to Planar Ionosphere
As indicated by initial observations

- Ionospheric Irregularities are common in area near geomagnetic equator

- Voids (Bubbles) in the ionosphere can range in size smaller than 200 km across

- Gradients in bubble walls can exceed 2 meters in 10 kms, to total ionopheric delay changes of 20 meters or more

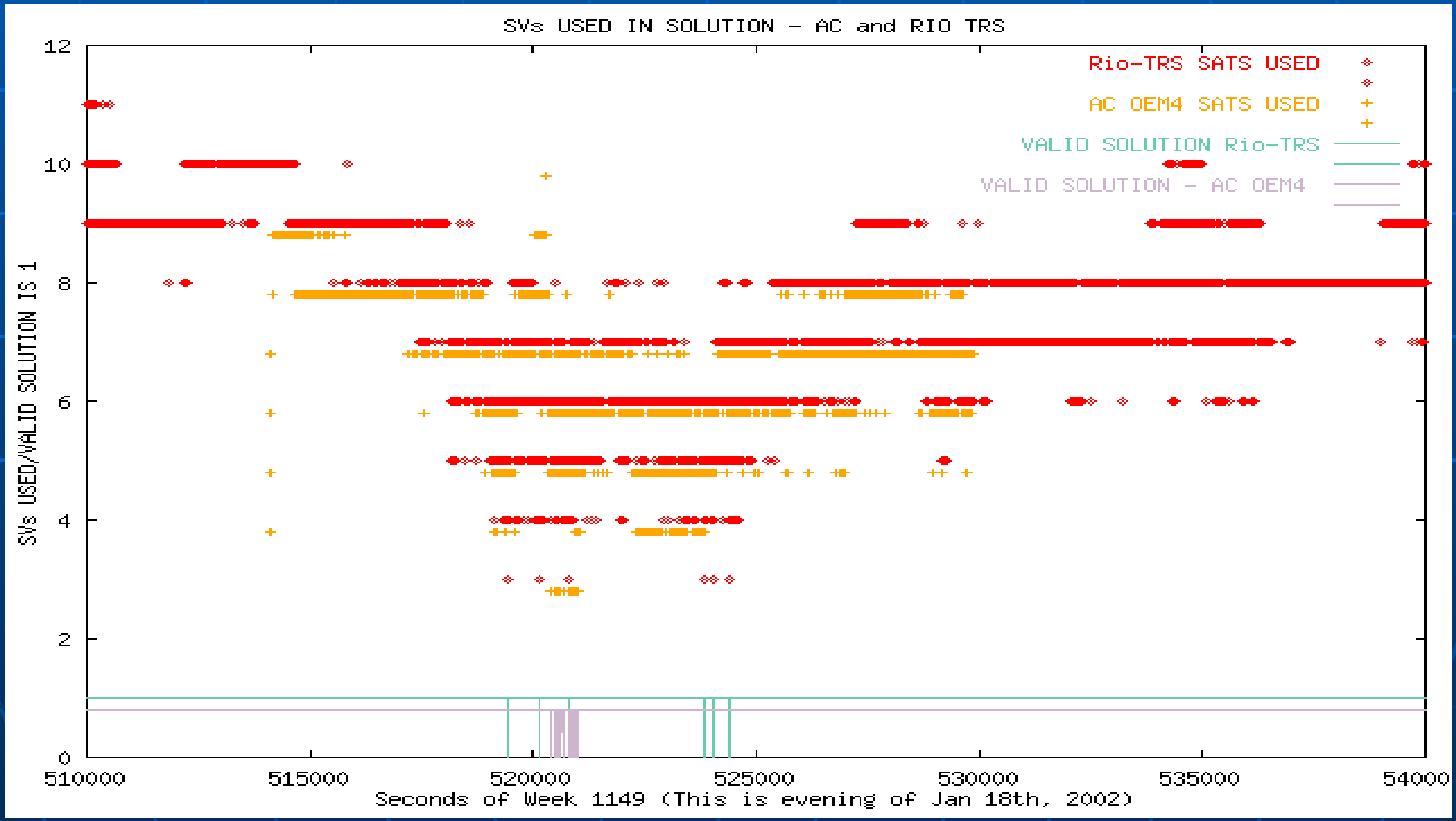
- Bubbles could be sufficient to require GIVEs in excess of 6 meters, and may either prevent use of LNAV/VNAV or greatly affect availability, or require alternate (undetermined) solution and proof of safety

Effects of Scintillation - I

- Equatorial Anomaly also gives rise to scintillation (phase and amplitude)
- Amplitude Scintillation – conceptually similar to multipath – constructive and destructive interference occurs due to different RF paths
- Scintillation can result in loss of GPS satellites for short durations – affecting the performance of GPS position determination in receivers
- Scintillation can result in loss of SBAS GEO (250 bit) correction and integrity messages, which could affect availability of SBAS NPA system

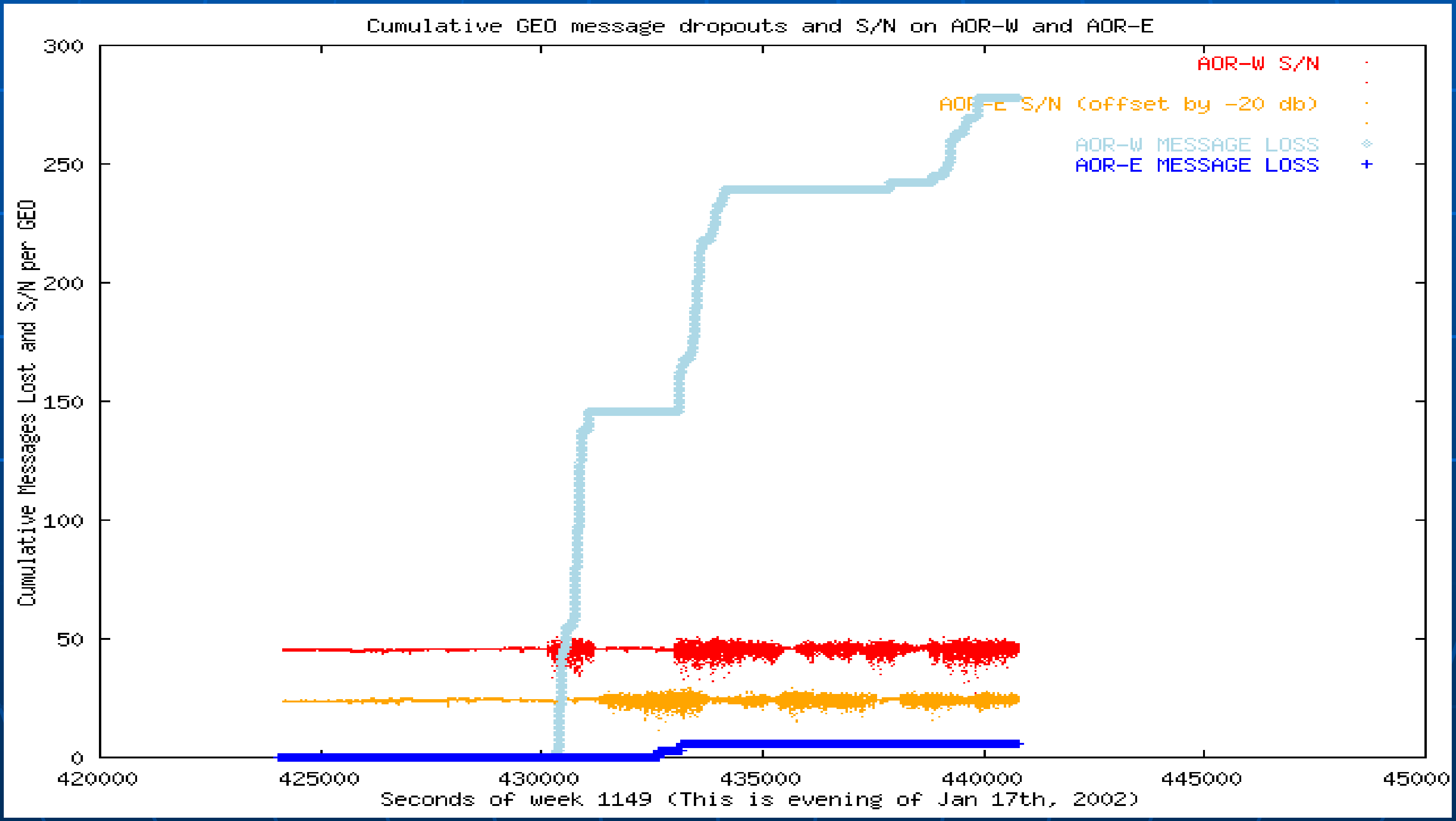
Effects of Scintillation on GPS and SBAS NPA

Example Data From the Brazil Flight Test



Effects of Scintillation on GPS and SBAS NPA

Example Data From the Brazil Flight Test



Effects of Scintillation -III

- Tentative Initial Conclusion:

- Simulating an NPA SBAS with the performance of the aircraft certified receiver and GEO messages being delivered from dual, well placed GEOs, the HPL should have remained under 556 meters, permitting continuous NPA operations during the severe scintillation which was observed on the nights of the flights

- To minimize and possible disruption of service on nights with equivalent or worse scintillation, detailed investigation should be focused on NPA receiver algorithms and performance in scintillation conditions, GEO message performance differences (as it could affect GEO placement), and SBAS ground infrastructure and algorithms (to insure operation under locally strong scintillation)

Future Plans

- Second Civil Frequency
  - Allow aircraft receiver to ***measure*** iono delay, so no necessity to have a planar ionosphere to interpolate Iono Grid Delays or bounds of error
  - GIVE would be likely be replaced by function (receiver noise/elevation)
  - Survey grade receivers (like WAAS reference station receivers) currently make L1/L2 measurements using cross correlation; this suffers power degradation and L2 is not a frequency in a protected frequency band

- Near-term more difficult for SBAS Precision Approach in areas near equator due to danger of equatorial anomaly, but little doubt in long term (12 yrs +), when aircraft receivers can measure delay using the second civil frequency (L5).

- Investigate near-term possibility of SBAS NPA with Baro-VNAV to enable LNAV/VNAV in Geomagnetic Equator areas